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Using Cover Crops to Recycle Nutrients in an Arkansas No-Till Corn System

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Using Cover Crops to Recycle Nutrients in an Arkansas No-Till Corn System

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by

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ABSTRACT

Cover crops can provide many benefits to cropping systems including erosion control, weed suppression, and increased soil organic matter. Regardless of the intended goal for using cover crops, the changes to the nutrient flux in a cropping system caused by cover crops retaining and recycling nutrients needs to be considered in order to maximize the productivity of the following commodity crops. This research encompassed complementary greenhouse, field, and laboratory experiments to evaluate nutrient uptake and release by tillage radish (*Raphanus sativus*) and cereal rye (*Secale cereale*) cover crops, as well as the subsequent early-season recovery of recycled nutrients by the following corn (*Zea mays*) crop. When grown under controlled greenhouse conditions, tillage radish and cereal rye cover crops recovered, at most, 38% of the applied fertilizer N, and most of the captured N was translocated and stored in the shoots, which produced greater biomass than the roots. Cereal rye generally recovered more N, P, K, and Zn than tillage radish due to greater biomass accumulation; however, by the V6 growth stage corn following tillage radish usually produced more dry matter and contained more N, P, K, and Zn than corn planted into cereal rye residue. Early season corn growth and nutrient uptake following cereal rye was often lower than that of corn planted into no cover crop. The fertilizer N recovery efficiency of cover crops grown in the field study was, at most, 60%, and the application of fertilizer N did not always increase corn nutrient uptake. Results from the laboratory incubation study revealed that tillage radish released available N earlier in the growing season than cereal rye residue. By the end of the incubation 43% of the total N (TN) contained in the residues was recovered as NO_3-N. Incorporating cover crop residues increased the rate at which NO_3-N accumulated during the later stage of the incubation trial (42 to 179

days). Based on results from this study, tillage radish cover crops provide a more optimum timing of nutrient release in alignment with early-season corn nutrient demand than cereal rye.

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Introduction and Literature Review

INTRODUCTION

Concerns about surface water contamination and soil health have prompted row crop producers to implement cover cropping and other conservation practices in their field management systems. The major benefit of cover cropping, erosion control, is tangible across cropping systems and environments throughout the U.S. (Martin and Cassel, 1992; Dabney et al., 2001; Kaspar et al., 2001). Other benefits, such as N recovery and cycling, vary greatly with management practices and production environments (Dabney et al., 2001; Fageria et al., 2005). A recent survey revealed that producers perceived the top three benefits of using cover crops to be improved soil health, minimizing yield variation for commodity crops, and increased commodity crop yields (CTIC, 2017). Successful utilization of cover crops involves setting specific goals for a cropping system and growing environment and implementing management practices that maximize the benefits from cover crops.

Many factors such as cover crop species, soil physical and chemical properties, preceding and following cash crops, and timing of cover crop planting and termination influence the efficacy of a cover crop system. Cereal rye (*Secale cereal* L.) is commonly grown by producers for its high biomass production and N scavenging abilities (Dean and Weil, 2009), and tillage radish (*Raphanus sativus* L.), also known as forage or daikon radish, is becoming increasingly popular for its high nutrient uptake and ability to penetrate restrictive soil layers in Mid-Atlantic fields (Dean and Weil, 2009; Chen and Weil, 2010); however, research on cover crops in Arkansas production systems is lacking. Farmers in the mid-South are particularly interested in knowing if tillage radish or cereal rye will efficiently recycle N in their cropping systems. This study was designed to evaluate the efficacy of tillage radish and cereal rye cover crops in recovering and releasing nutrients in a corn (*Zea mays* L.) production system.

Approximately 5.4 million ha of land in Arkansas is utilized by 42,000 farms (USDA-National Agricultural Statistics Service, 2018). Arkansas is the leading rice (*Oryza sativa* L.)-producing state, ranks 11th in soybean (*Glycine max*) and 20th in corn production in the United States (USDA-National Agricultural Statistics Service, 2018). Corn in Arkansas is usually planted on raised beds, which allows for furrow irrigation, the dominant irrigation method for corn production in the mid-South. Due to high N requirement by corn and generally low native soil N, fertilizer N recommendations for high yielding corn range from 245 kg N ha^{-1} on silt loam soils to 325 kg N ha^{-1} on clay soils (Kelley and Lawson, 2015). Nitrogen fertilizer is typically applied to corn in split applications as urea, with one-fourth to one-third of the recommended N rate applied at planting and the remaining fertilizer N applied as a sidedress near the V6 growth stage (Espinoza and Ross, 2008). Recommended rates of phosphorus (P) and potassium (K) fertilizers for corn range from 56 to 112 kg P_2O_5 ha^{-1} and 56 to 224 kg K_2O ha^{-1}, respectively (Espinoza and Ross, 2008). Zinc (Zn) is a likely micronutrient deficiency in corn produced in Arkansas due to alkaline pH, common of many soils in the state, and 11 kg Zn ha^{-1} is typically recommended to correct the deficiency in corn (Espinoza and Ross, 2008).

Soils on which most row crops are produced in Arkansas range from silt loam to clay in texture. Most of these soils are poorly drained, which is ideal for flooded rice production and waterfowl habitat but can be problematic for other crops. Surface crusting is prevalent in silt loam soils across the state and is exacerbated by relatively low (< 0.5%) organic matter content in most soils. Due to limited availability (approximately 59 days in an average year and 75 days in a good year between April and June) of suitable working days in the spring, farmers in Arkansas take advantage of short periods of adequate weather and soil conditions in the fall to prepare fields for spring planting of summer cash crops (Ross et al., 2008; Griffin and Kelley, 2010). Although field preparation in the fall saves time for farmers in the spring, this practice leaves soils bare during the winter, which renders the soil susceptible to erosion and runoff. Soil removed from these fields via erosion or runoff also removes nutrients from fields and can pollute nearby water sources.

Concerns about soil health and water quality, especially along the Mississippi River, have encouraged Arkansas farmers and researchers to search for solutions. Cover crops have gained attention as a conservation tool to mitigate these problems by reducing erosion and runoff, improving soil stability, and sequestering nutrients. Cover crops have been studied for many years in the other regions of the United States, but research is needed to determine the effectiveness of various cover crop management techniques in Arkansas production systems.

LITERATURE REVIEW

General Cover Crop Effects

Cover crops can be utilized in a many agricultural systems to provide a variety of benefits. Cover crop acreage across the US has steadily increased since 2012 (CTIC, 2017) as producers learn of the benefits associated with cover crops and as more relevant information is available for producers. Unfortunately, research and relevant recommendations for growing cover crops in Arkansas is minimal. Much of the current cover crop research is particular to the Midwest, mid-Atlantic, and southeast regions of the United States. These regions have distinct climates, but Arkansas lies in a transition zone between Midwestern and southern climates, making winter weather conditions more dynamic from year to year. Most of the research about cover crops in row crop systems in the Midwest and mid-Atlantic regions, such as that of Dean and Weil (2009) and Kristensen and Thorup-Kristensen (2004), has focused on cover crops planted in late summer, while cover crops in Arkansas are planted in the fall and grown through the winter. There is a lack of research on cover crops in Arkansas and the studies and management practices in other regions may not yield the same results in Arkansas, but the basic understanding of cover crop effects from research in other regions can be used by researchers to develop hypotheses and formulate studies particular to Arkansas production systems.

Cover crops play a critical role in reducing erosion, suppressing weeds (Creamer et al., 1996; Carrera et al., 2004; Lawley et al., 2011; 2012), and improving soil quality over time (Karlen et al., 1994). Planting crops for ground cover during seasons when cash crops are not grown decreases soil and nutrient loss caused by wind erosion and water runoff (Kaspar et al., 2001). When managed correctly, cover crops can also diminish weed pressure through competition, allelopathic compounds, or a combination of these methods (Lawley et al., 2011;

2012). A major long-term benefit of utilizing cover crops includes improved soil quality as a result of increased organic matter, soil structure improvement, and soil nutrient conservation (Karlen et al., 1994). Organic matter increases cation exchange capacity (CEC), enhances soil aggregate stability, and aids in nutrient and water retention. Dapaah and Vyn (1998) found that aggregates were more stable in soil with cover crops than in soil without cover crops; specifically, oilseed radish (*Raphanus sativus* L.) increased soil aggregate stability more than annual ryegrass (*Lolium mulitflorum* L.) and red clover (*Trifolium pratense* L.).

The effects of cover crops can also be reflected in the growth and productivity of cash crops grown after cover crops. Cover crops have been shown to have varying effects on the yield and growth of subsequent cash crops, depending on the management system and cover crop species. In a study by Dapaah and Vyn (1998), corn was the tallest and produced the greatest yield following red clover, while corn grown after annual ryegrass was the shortest and produced the lowest yield; the authors concluded that greater mineralization of organic N in red clover and greater immobilization and delayed release of plant-available N in annual ryegrass contributed to the observed differences in corn height and yield. Williams and Weil (2004) found that no-till, dryland soybean yield significantly increased following a forage radish/cereal rye mixture compared to rye monoculture and no cover. The enhanced soybean performance was attributed to greater soil moisture retention due to thick cover from rye biomass and improved uptake of deep soil water by soybean roots which bypassed compacted plow pan layers through root channels formed by forage radish.

Nutrient Cycling in Cover Crops

Cover crops also function as catch crops to reduce nutrient loss by recovering and releasing nutrients for subsequent crop use. Evaluating cover crop sequestration of N is particularly important since N is usually the most limiting nutrient in cereal cropping systems and is very susceptible to loss, which can have negative environmental consequences and reduce soil productivity. Many studies have examined the effectiveness of cover crops in mitigating N loss from agricultural soil. Aronsson and Torstensson (1998) found N leaching was decreased 40 to 50% under catch crops compared to a fallow control; the authors also observed a greater increase in subsequent crop yields after catch crops than after fallow. Jackson et al. (1993) similarly showed that cover crops nearly depleted NO_3-N from 82.5 to 1.7 μg NO_3-N g^{-1} soil and 66.8 to 6.3 μg NO_3-N g^{-1} soil in the 0 to 15-cm and 15 to 30-cm depths, respectively.

Nutrients recovered by cover crops are released upon decomposition and can be mineralized for uptake by subsequent crops, which can impact the yield and fertilizer requirements of following cash crops (Kuo and Jellum, 2002; Andraski and Bundy, 2005). Depending on the availability of nutrients and the crop species grown, nutrients recycled from cover crops can provide N credits, which decreases the fertilizer needs and increases the yield of some crops (Kuo and Jellum, 2002; Andraski and Bundy, 2005). Andraski and Bundy (2005) reported that oat (*Avena sativa* L.), winter triticale (×*Triticosecale*), and cereal rye cover crops lowered the optimum N rate recommendations by an average of 32 ± 8 kg N ha^{-1} and increased corn yields by an average of 1.4 ± 0.3 Mg ha^{-1} in two out of three years. In a study by Kuo and Jellum (2002), corn yields without fertilizer N application averaged over four site-years were 14.5, 9.8, 9.5, and 8.8 Mg ha^{-1} following hairy vetch (*Vicia villosa* Roth), cereal rye, no cover crop control, and Italian ryegrass (*Lolium multiflorum* Lam), respectively.

Tracing Nitrogen Cycling in Cover Crops

Uptake and release of N by various cover crops has been examined in an assortment of cropping systems. A number of indirect and direct methods for quantifying the amount of N recovered and released by cover crops has been used in the literature. Indirect procedures include the difference method, which involves estimating the fertilizer N uptake from the difference in total N uptake between crops that received fertilizer N and control crops that did not receive fertilizer N (Roberts and Janzen, 1990). While the difference method is a relatively inexpensive and simple method, errors could arise from native soil N transformations and losses. Labelling fertilizer with a ^{15}N isotope provides a direct method for tracing the fate of N in a cropping system. This method involves applying N fertilizer with a known atom percent of ^{15}N and measuring the amount of ^{15}N in plant biomass. Fertilizer N uptake can then be calculated using Eq. 1, where *FN* is the uptake of ^{15}N-enriched fertilizer (kg N ha^{-1}), TN is the total N (kg N ha^{-1}) in the sample (calculated by multiplying the biomass dry weight by the percent of total N in the sample), *a* is the excess atom percent ^{15}N in the fertilizer, *b* is the background atom percent ^{15}N (atom percent ^{15}N of unfertilized control standards), and *c* is the atom percent ^{15}N in the sample (Hauck and Bremner, 1976).

$$FN = \frac{(TN)(c-b)}{a} \qquad [1]$$

Fertilizer N recovery efficiency is quantified using Eq. 2, where *FN* is the uptake of ^{15}N-enriched fertilizer (kg N ha^{-1}) and *f* is the amount of N fertilizer applied (kg N ha^{-1}) (Hauck and Bremner, 1976).

$$\%\ Fertilizer\ N\ Recovered = \frac{FN}{f} \times 100 \qquad [2]$$

Due to its high sensitivity in distinguishing between native soil N from fertilizer N and lack of radioactive emissions, ^{15}N isotope tracing has been utilized in a variety of agronomic field studies. One drawback from using ^{15}N-enriched fertilizer is the high cost of the materials, which often reduces the scale of field research to microplots and limited treatments.

Mineralization of N from Cover Crop Residue

Mineralization of plant residue plays a vital role in the cycling of nutrients and other chemical compounds in a cropping system. This process involves the breakdown of organic nutrients into inorganic forms by soil microorganisms, which occurs in two major steps. The first step, aminization, involves the transformation of organic N into amino-N (R-NH_2) with the production of carbon dioxide (CO_2) and energy (Mullen, 2011). In the second step, ammonification, the amino-N is converted into ammonia (NH_3) and energy is released; water then reacts with NH_3 to yield ammonium-N (NH_4^+) and hydroxide (OH^-) (Mullen, 2011). The inorganic NH_4^+ released into the soil can then be recovered by plants, exchanged with other cations on the soil colloid, or transformed into other forms of N, such as nitrate (NO_3^-).

Mineralization varies with plant residue composition, residue management, and environmental conditions. The biochemical composition or quality of plant residue greatly influences the rate at which plant residue is broken down and processed (Bending et al., 1998). Complex biochemical compounds, such as lignin and cellulose, are very stable and not easily degraded or processed by microbes. Residue, such as grasses and mature plants, with higher concentrations of these compounds undergo mineralization and release nutrients much slower than residue containing less stable compounds (Wagger, 1989a; Mullen, 2011). Bending et al. (1998) observed that soluble phenolic and water soluble-N concentrations in plant residue largely controlled early-N mineralization, while cellulose content regulated N mineralization during later stages of decomposition. In a study by Wagger (1989a), the cellulose, hemicellulose, and lignin concentrations generally increased as cover crops (cereal rye, crimson clover (*Trifolium incarnatum*), and hairy vetch) matured, but the concentrations of cellulose and hemicellulose were consistently higher for cereal rye than crimson clover and hairy vetch throughout the study. As a result, cereal rye residue decomposed and released N more slowly than other cover crops.

From an agronomic perspective, mineralization of organic N to plant-available forms is of great interest. Cycling of N from plant residue through mineralization is impacted by the amount of C relative to the amount of N in the residue, which is denoted as the C:N ratio of the plant material. Nitrogen availability is limited to soil microbes when the C:N ratio of plant material is large (approximately >30:1), which results in net immobilization of N rather than mineralization (Aulakh et al., 1991; Mullen, 2011). Net mineralization occurs and N is released when organic N is abundant and the C:N ratio of the residue is small (approximately <20:1) (Wagger, 1989a; Aulakh et al., 1991; Mary et al., 1996; Mullen, 2011). Management of cover crop residue, particularly the level of incorporation, also affects the mineralization rate of residue in a cropping system. Retaining cover crops on the surface without incorporating the residue results in reduced mineralization to varying degrees (Aulakh et al., 1991) due to poor contact with the soil matrix, which is generally where microorganisms responsible for plant decomposition reside (Henriksen and Breland, 2002). Incorporation with tillage relocates residue below the soil surface and aerates the soil, which increases microbial activity and mineralization (Mullen, 2011). In a study by Aulakh et al. (1991), incorporating low C:N residue (hairy vetch) resulted in an increase in mineralization from 36% to 51% of mineral N, while incorporating high C:N residue (wheat (*Triticum aestivum* L.), corn, and soybean) gave rise to greater immobilization of N.

Environmental conditions, such as soil moisture and temperature, also regulate the mineralization of organic material. The majority of soil microorganisms responsible for mineralization of crop residue are aerobic and require an adequate amount of oxygen in order to perform certain biochemical processes. Microbial activity in the soil is maximized under ideal moisture conditions and is slowed greatly when soil is too dry or too saturated. Soil temperatures in an optimum range are also needed to encourage soil microorganism activity and the mineralization of organic matter. In a study by Cassman and Munns (1980), soils were incubated in the laboratory at four temperatures (15, 20, 25, and 30°C) with six moisture levels (10, 30, 70, 200, 400, and 1,000 kPa); the authors observed that maximum mineralization occurred at 30 kPa and then declined with increasing matric potential across all temperatures. Furthermore, mineralization was higher at 30°C and decreased with temperature for all soil moisture treatments.

Factors Affecting Cover Crop Efficacy

Producers should consider several factors that influence cover crop efficacy in order to acquire the maximum benefits from cover cropping. Understanding factors, such as cover crop species, planting and termination timing, and subsequent cash crops, could help farmers manage cover crops efficiently in order to achieve a desired goal. Selecting the appropriate cover crop species for a cropping system and growing environment is crucial since cover crop species vary greatly in growth, development, and biomass production (Thorup-Kristensen, 2001; Kristensen and Thorup-Kristensen, 2004). Cover crop species can roughly be categorized as legumes and non-legumes, which includes other broadleaves, grasses, and cereal grains. Although seed costs for legumes are usually higher than grains and grasses, legumes can reduce fertilizer N requirements in some operations (Brennan and Boyd, 2012). Legumes can contribute additional N to a soil system by converting atmospheric N_2 to NH_3 in the soil, which is converted into plant-available forms (NH_4^+ and NO_3^-) for the legume to use; nitrogen is then released into the soil upon mineralization of the organic N contained in the legume residue. Increased N fertility through biological-N fixation by legume cover crops can decrease the amount of fertilizer N needed for subsequent cash crops to produce sufficient yields. Decker et al. (1994) showed that legume cover crops decreased the fertilizer N requirement to produce maximum corn yields from 10 to 75 kg N ha^{-1}.

Cover crop species also differ in biomass production and root growth, which could impact weed control, nutrient sequestration capacity, and soil surface management. Most cereal grain and grass cover crops are effective at weed suppression, erosion control, and nutrient scavenging due to high biomass production (Shipley et al., 1992). High biomass residue on the soil surface can also impede planting and germination of following cash crops in no-till systems. Some non-legume broadleaf cover crops, such as *Brassicas*, may not produce as much biomass as grasses and grains but can offer similar benefits without restricting establishment of subsequent crops. *Brassicas* establish canopy coverage and root systems quickly, which provides early competition with weeds and uptake of residual soil nutrients (Jackson et al., 1993).

Variations in root growth can also contribute to differences in nutrient scavenging abilities among cover crop species (Thorup-Kristensen, 2001; Kristensen and Thorup-Kristensen, 2004). Kristensen and Thorup-Kristensen (2004) measured the root growth of three cover crop species, Italian ryegrass, cereal rye, and fodder radish (*Raphanus sativus* L. var. *oleiformis* Pers.), and found that fodder radish roots grew deepest at 2.4 m compared to Italian ryegrass at 0.6 m and cereal rye at 1.1 m. Due to greater rooting depth, fodder radish was able to scavenge more soil NO_3-N than the other cover crop species, which resulted in only 18 kg N ha^{-1} of residual NO_3-N remaining in the soil after fodder radish compared to 59 and 87 kg N ha^{-1} of residual soil NO_3-N following cereal rye and Italian ryegrass, respectively.

Another consideration to make when planting cover crops is whether to plant cover crop species in a monoculture or to utilize two or more species in a blend. A cover crop monoculture offers convenience to producers at planting and termination, as well as a uniform stand. Cover crop blends increase biological diversity and can decrease risk by capitalizing on complementary benefits from different species (Kuo and Sainju, 1998; Teasdale and Abdul-Baki, 1998). Weed biomass and emergence were significantly reduced in cover crop mixtures containing cereal rye and crimson clover or cereal rye and hairy vetch compared to the legume monocultures in a study by Teasdale and Abdul-Baki (1998). Kuo and Sainju (1998) also showed that adding a legume to a cereal grain cover crop mixture lowered the C:N ratio, which improved the mineralization potential of nutrients sequestered by the cover crops.

Tillage practices should also be suitable for a specific soil and should complement the cover cropping system. Conventional tillage creates a clean surface for planting, but this practice expedites organic matter degradation and reduces soil structure by disrupting aggregates and forming a restrictive plow layer over time (Mazzoncini et al., 2011). These consequences are counterproductive to the objectives of cover cropping. Conservation tillage enhances the benefits of cover cropping by retaining residue on the soil surface and minimizing soil disturbance, which improves organic matter and soil structure (Mazzoncini et al., 2011). Methods of conservation tillage range from no-till, where the soil is not disturbed by tillage and seeds are directly drilled into the soil, to strip tillage, where only a shallow strip of soil is turned in which to place the seed rows. Although no-till offers many benefits, this practice may not be suitable for use on high residue cover crops due to limited seed-to-soil contact and impeded germination (Mitchell and Teel, 1977).

Since maximizing the productivity and efficiency of cash crops is a major objective for row crop producers, the cash crops that follow cover crops should be taken into consideration when designing a cover crop system. Common disease and pest issues that can potentially reduce yield or quality for a specific cash crop are important factors when selecting cover crop species. Pest and disease cycles can be disturbed by introducing cover crops that differ from the cash crop in pest and disease susceptibility and by using cover crop species with inherent pest or disease suppression abilities (Altieri, 1999; Larkin et al., 2010). Larkin et al. (2010) observed a 12% average decrease in black scurf and a 7.2% average reduction in a long-term potato (*Solanum tuberosum* L.) study due to the addition of a cereal rye cover crop; the authors attributed the decline in potato diseases to a disruption in the disease cycles with the introduction of the cover crop.

Pest and disease infestation can be avoided by effectively killing cover crops within a timing window that is suitable for the following cash crop. In climates like that of Arkansas, warmer late winter and early spring temperatures are adequate for the growth and reproduction of some pests as they feed on live plants, such as winter cover crops. Winter cover crops and other winter plants retained as residue in conservation tillage systems can create a "green bridge" by providing hosts for pests and diseases to overwinter and infest the following cash crop (Smiley et al., 1992; Babiker et al., 2011). The complete termination of winter cover crops and other winter plants before planting the cash crop eliminates the "green bridge" by destroying the hosts for overwintering inoculum and pests (Smiley et al., 1992; Babiker et al., 2011). Babiker et al. (2011) found that increasing the time interval between glyphosate applications on winter weeds or volunteer crops and barley (*Hordeum vulgare* cv. Baronesse) planting decreased infection of Rhizoctonia root rot (*Rhizoctonia solani* and *Rhizoctonia oryzae*) in barley.

The persistence of chemicals such as allelopathic chemicals from plants and chemical herbicides plays an important role in determining selection and termination of cover crop species. Allelopathic chemicals are excreted by some plants and have the potential to inhibit germination of some seeds (Creamer et al., 1996). If these chemicals persist in the soil long after cover crop termination, the germination of subsequent crop seeds could also be impaired (Raimbault et al., 1990). Corn yield was consistently lower following a cereal rye cover crop than no cover crop, regardless of tillage, in a study by Raimbault et al. (1990). The authors concluded that reduction in corn yield was likely due to the secretion of phytotoxins from cereal rye residue, which delayed corn development.

Mode of action and persistence of chemical herbicides used to terminate cover crops or to control weeds in the cash crop should also be considered. A suitable chemical herbicide that completely terminates the cover crops should be applied in advance of cash crop planting to prevent impediment during planting and to avoid competition with young cash crops (Constantin et al., 2008). Constantin et al. (2008) recommended terminating cover crops at least 2 or 3 weeks prior to planting corn to avoid inconsistent germination and delayed development of corn. The species and appropriate timing window for establishment of the following cash crop should be taken into consideration when selecting an herbicide to terminate cover crops. Herbicides applied to cover crops near planting of the following crop could result in cash crop injury and yield loss (Nascente et al., 2013). In a study by Nascente et al. (2013), delaying glyphosate application to cover crops near the planting of no-till rice significantly decreased rice seedling dry matter and number of panicles m^{-2} and resulted in an average yield loss of 544 kg ha^{-1}. The chemical herbicide program for weed control in the cash crop should be considered when selecting cover crop species that precede the cash crop. Application of in-season herbicides on cash crops could result in reduced growth or delayed establishment of the following crop (Rogers et al., 1986; Walsh et al 1993). Walsh et al. (1993) showed that carryover of metribuzin + chlorimuron and chlorimuron applied to soybeans approximately 4 months prior to cover crop planting significantly reduced alfalfa (*Medicago sativa*) biomass compared to the untreated control, whereas hairy vetch and cereal rye cover crops were relatively undamaged by herbicide carryover.

Timing cover crop planting and termination is critical for extracting the maximum benefits from cover cropping. Planting and termination timing of cover crops affects the amount of biomass and nutrients cover crops can accumulate, as well as the synchronization of nutrient release from cover crops and uptake by subsequent crops (Clark et al., 1997). In order to achieve sufficient weed suppression and erosion control early, cover crops should be planted soon after harvest of the preceding cash crop. Proper timing of cover crop termination is also important for synchronizing nutrient release from cover crops with nutrient uptake by the subsequent cash crop (Wagger, 1989a, 1989b; Clark et al., 1997). Date of planting and termination influence biomass accumulation and amount of nutrients sequestered by cover crops (Clark et al., 1997). In a study by Clark et al. (1997), cover crop biomass and N accumulation increased as cover crop termination was delayed in a no-till corn system.

Cereal Rye

Cereal rye is a common winter cover crop grown for its high biomass production and extensive root system. These characteristics make cereal rye effective at reducing erosion and leaching nutrient loss by capturing mobile residual soil nutrients (McCracken et al., 1994; Sainju et al., 1998; Dean and Weil, 2009). Cereal rye decreased NO_3-N leaching in a sweet corn-broccoli (*Brassica oleracea* var. *italica* Plenck) rotation by 22 to 58% in a study by Brandi-

Dohrn et al. (1997). Heavy biomass cover can also pose some problems for the emergence and growth of subsequent crops, especially in no-till systems. Lawley et al. (2011) observed a decrease in plant population when corn was no-till drilled into cereal rye residue. The authors attributed the diminished stand to cereal rye residue obstructing seed-to-soil contact and seedling emergence. This study agreed with Mitchell and Teel (1977), who found that thick coverage by cereal rye residue resulted in inconsistent and reduced corn stands in a no-till system.

Cereal rye is effective at sequestering excess N, but release of the recovered N can be delayed due to immobilization or slow mineralization from cereal rye residue which typically has a high C:N ratio. Kuo and Sainju (1998) reported that N immobilization potential increased as the proportion of cereal rye and C:N ratio increased in a hairy vetch mixture; net immobilization rate ranged from 0 mg kg^{-1} $week^{-1}$ under hairy vetch alone (with C:N ratio of 10:1) to 36.7 mg kg^{-1} $week^{-1}$ under cereal rye alone (with C:N ratio of 23:1). Ranells and Wagger (1996) observed that N was released much slower from a cereal rye monoculture (24 kg N ha^{-1} over 8 weeks) than from a cereal rye-hairy vetch mixture (108 kg N ha^{-1} over 8 weeks). Immobilization or delayed release of N from cover crop residue can increase the fertilizer N needs and potentially decrease the following cash crop's productivity. (Wagger, 1989b). In a study by Wagger (1989b), corn following legume cover crops (hairy vetch and crimson clover) produced significantly more dry matter than corn following cereal rye. The author's findings suggested that cereal rye immobilized more N due to a relatively wide C:N ratio and released N more slowly than the legume cover crops.

Tillage Radish

Tillage radish is a forage or daikon radish named for its enlarged root that is capable of penetrating restrictive soil layers and leaving large channels after decomposing. This process of biodrilling improves water infiltration and provides channels through which subsequent crop roots can grow and bypass restrictive layers. Chen and Weil (2010) observed that forage radish was more effective at penetrating compacted soil than cereal rye, with more than twice the number of roots at the 15 to 30-cm depth under high compaction. Tillage radishes belong to the *Brassica* family which grow quickly and establish extensive root systems and canopy coverage faster than grasses (Jackson et al., 1993). These characteristics make tillage radishes effective at suppressing weeds throughout the fall and into early spring (Lawley et al., 2011) and sequestering soil nutrients rapidly. The deep roots can recover nutrients and release the sequestered nutrients directly into the root zone for subsequent crops (White and Weil, 2011). Kristensen and Thorup-Kristensen (2004) reported that residual soil NO_3-N decreased significantly under fodder radish with 18 kg N ha^{-1} left in the soil compared to 59 and 87 kg N ha^{-1} under cereal rye and Italian ryegrass, respectively. The authors attributed the lower residual NO_3-N levels under fodder radish to greater rooting depths compared to cereal rye and Italian ryegrass. Tillage radish residue typically has low to moderate C:N ratios (9:1 to 25:1 (Ruark et al., 2018)), which facilitate net mineralization of organic N to plant available forms (Magid et al., 2004). Tillage radish has also been shown by White and Weil (2011) to be effective in cycling P in the Mid-Atlantic region of the U.S.; the authors found that soil-test P values were much greater in the soil immediately surrounding tillage radish root holes compared to the bulk soil and soils where tillage radish was not grown.

OBJECTIVES

Limited research on nutrient cycling in cover crops in Arkansas production systems has been conducted; therefore, this research was established with complementary greenhouse, field, and laboratory experiments to address the gap in knowledge about cover crop contributions to nutrient fluxes in row crop systems. The objectives of this study are to 1) quantify the mass and efficiency of ^{15}N-enriched fertilizer uptake by cereal rye and tillage radish cover crops grown in two different field soils under ideal greenhouse conditions, to 2) evaluate the uptake and release of ^{15}N-labelled fertilizer by cereal rye and tillage radish cover crop to the following corn crop under no-till field conditions, to 3) assess the uptake of P, K, and Zn by cereal rye and tillage radish cover crops and utilization by the following corn crop under no-till conditions, and to 4) investigate the influence of residue incorporation on available N release by tillage radish and cereal rye cover crops.

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CHAPTER 2

^{15}N Fertilizer Recovery and Partitioning by Cover Crops under Controlled Environmental Conditions

ABSTRACT

Cover crops have the potential to decrease residual-nitrogen (N) losses from agricultural soils by capturing and storing excess N between cash crops. The efficacy of cover crops to recover and accumulate residual N is influenced by cover crop species, biomass accumulation, root growth, climate, soil properties, and N availability. This study was established to assess the effect of cover crop species and N rate on the accumulation and partitioning of biomass and ^{15}N fertilizer by cover crops produced under controlled environmental conditions. Cereal rye (*Secale cereale*) and tillage radish (*Raphanus sativus*) cover crops were grown in monoculture and in a blend under greenhouse conditions in two soils. Urea enriched with ^{15}N (3.0 atom %) was applied to cover crops at rates of 0, 34, and 67 kg N ha^{-1}. Shoot dry matter production and N accumulation exceeded that of roots for both cover crops. Fertilizer N uptake increased as application rate increased, and the greatest overall recovery by the cover crops was 38% of the applied fertilizer N. Tillage radish shoot biomass nearly doubled that of cereal rye (1585 kg ha^{-1}) when grown in monoculture in the Captina soil (Fine-silty, siliceous, active, mesic Typic Fragiudults), but cover crops stored similar quantities of total N (TN) in the shoots. Cover crops grown in monoculture in the Roxanna soil (Coarse-silty, mixed, superactive, nonacid, thermic Typic Udifluvents) accumulated similar amounts of biomass and TN in the shoots; however, cereal rye root biomass was twice that of tillage radish (568 kg ha^{-1}) when 67 kg N ha^{-1} was applied, which resulted in greater root TN storage than in tillage radish roots. Results from this study reflect the capacity for N sequestration by cover crops, which is largely determined by biomass production and N availability, and most of the captured N is translocated and stored in the shoots. Furthermore, cereal rye did not surpass tillage radish in shoot biomass or shoot N

storage under warm temperatures, but cereal rye can compensate for slow aboveground growth with greater root biomass than tillage radish.

INTRODUCTION

Nitrogen is one of the most important nutrients for crop growth, and is usually required in the greatest quantities by crops for maximal biomass and grain production. Unfortunately, residual N remaining in the soil after cash crop harvest is susceptible to loss through erosion, runoff, and leaching, especially when the soil is left bare. Off-site movement of N from agricultural fields contributes to surface and ground water contamination, as well as diminished soil fertility and productivity (Frye et al., 1982). Cover crops grown between commodity crops can be used to mitigate surface and subsurface losses of residual N. Cover crops decrease the potential for surface loss of N by shielding surface particles from wind and reducing the velocity of water moving into and across the soil surface; thus, cover crops improve infiltration and minimize erosion and runoff (Kaspar et al., 2001). Removal of sediment and adsorbed N due to erosion is further reduced as soil aggregates are stabilized by cover crop roots and organic matter additions from cover crop residue (Kaspar et al., 2001).

Cover crops provide additional safeguards against N losses by serving as sinks for residual soil NO_3-N that could otherwise be lost from bare or fallow soils through leaching or denitrification (Jackson et al., 1993). Often referred to as “catch crops”, cover crops minimize NO_3-N leaching losses by recovering and storing residual NO_3-N in dry matter until the cover crop residue is mineralized (Brandi-Dohrn et al., 1997; Dabney et al., 2010). Brandi-Dohrn et al. (1997) showed that cereal rye reduced NO_3-N leaching by 33% in a sweet corn (*Zea mays* L.)-winter fallow system and by 62% in a broccoli (*Brassica oleracea* var. *italic*)-winter fallow system. Similarly, cereal rye cover crops planted immediately after harvest of no-till corn were responsible for reducing NO_3-N leaching by 80% and groundwater NO_3-N concentrations by 60% over nine years in the Coastal Plain region of the Chesapeake Bay (Staver and Brinsfield, 1998).

The efficacy of cover crops in capturing nutrients and reducing nutrient loss can be largely attributed to the rate and amount of dry matter accumulation (Sainju et al., 1998; Gastal and Lemaire, 2002; Kristensen and Thorup-Kristensen, 2004), which is affected by cover crop species, management, and growing conditions (Dabney et al., 2010). Shipley et al. (1992) concluded that grass cover crops are more effective at sequestering residual N than legumes due to deeper and more rapid root growth, as well as the ability to withstand colder temperatures by undergoing dormancy. The authors observed that cereal rye and annual ryegrass (*Lolium Multiflorum* Lam.) sampled in the spring captured 60% and 40% of the residual fertilizer N remaining after the previous corn crop, respectively, whereas native cover crops (chickweed (*Stellaria media* L.)), hairy vetch (*Vicia villosa* Roth), and crimson clover (*Trifolium incarnatum* L.) removed less than 10% of the remaining corn fertilizer N. Sainju et al. (1998) confirmed with a minirhizotron that grass cover crops like cereal rye had significantly greater quantity and length density of roots in the top 50 cm of soil compared to legumes like hairy vetch or crimson clover. In the same study, cereal rye recovered significantly more soil NO_3-N than hairy vetch and crimson clover, which the authors attributed to greater root growth and aboveground dry matter production by cereal rye.

Regardless of species, nutrient acquisition by cover crops can be limited by management practices or growing conditions that reduce growth and overall biomass production. Cover crops planted earlier have more time to establish extensive root systems, provide more soil surface coverage, and capture a greater amount of nutrients than cover crops planted later (Clark et al., 1997; Vos and van der Putten, 1997). Vos and van der Putten (1997) found that for every day that cover crop (cereal rye, forage rape (*Brassica napus* ssp. *oleifera* (Metzg.) Sinsk), and oilseed radish (*Raphanus sativus* spp. *oleiferus* (DC.) Metzg.)) planting was postponed after the optimal planting date (late August), cover crop N uptake decreased by 0.34 g m^{-2}, on average. Similarly, winter cover crops that are terminated later achieve greater growth and nutrient uptake in the spring than early terminated cover crops (Clark et al., 1997). A study by Clark et al. (1997) in Maryland showed that hairy vetch and cereal rye cover crops accrued more dry matter and residual N as termination was postponed.

Environmental conditions, such as temperature, can also limit cover crop growth and nutrient acquisition. Some cover crop species, such as tillage radish, are prone to winterkill during the vegetative stage under sustained low temperatures (White and Weil, 2010); early termination under such conditions reduces nutrient uptake for cold-sensitive cover crops and increases the risk for premature leaching of nutrients from cover crop residue (Miller et al., 1994). An evaluation of N and P leaching from cover crops subjected to freezing (-18°C) by Miller et al. (1994) demonstrated that the concentration of NO_3-N in the leachate from oilseed radish after freezing was greater than that from red clover (*Trifolium pratense* L.) or annual ryegrass. Winter-hardy plants, on the other hand, are able to undergo dormancy during periods of low temperatures and produce a majority of total growth in late winter or early spring (Finney et al., 2016). As a result, cold-tolerant cover crops, such as cereal rye, often produce more biomass and sequester a greater amount of nutrients than cover crops that winterkill (Finney et al., 2016).

The capacity for biomass accumulation and N acquisition by cover crops can be dependent on the physical soil properties and N supply. Soil compaction is known to impede root growth, which limits plant growth and nutrient uptake (Voorhees, 1985; Petelkau and

Dannowski, 1990); however, some cover crop species are capable of penetrating restrictive soil layers and capturing nutrients from deeper horizons. Chen and Weil (2010) showed that taprooted *Brassica* cover crops (forage radish and rapeseed (*Brassica napus*)) were more effective at penetrating compacted soil horizons than fibrous rooted grass cover crops (cereal rye) due to thicker roots. The amount of N available to cover crops also impacts cover crop growth and N recovery. Vyn et al. (2000) noted that biomass accumulation and N uptake of cover crops planted after cereal grain (winter wheat (*Triticum aestivum* L.)) harvest was limited by N availability, especially for non-legume cover crops (cereal rye, oilseed radish, and oats (*Avena sativa* L.)).

Evaluating the capacity for N recovery and partitioning by cover crops is important for understanding how cover crops differ in ability to reduce N losses from soil. Applying ^{15}N-labeled fertilizer can provide accurate differentiation of N sources captured and partitioned by cover crops. Many studies have evaluated the scavenging capabilities of cover crops in fields; however, the uptake and partitioning of N to the shoots and roots of cover crops under controlled environmental conditions have not been extensively investigated or reported. Controlling environmental conditions in a greenhouse can diminish the effects of varying temperature and moisture on cover crop growth and nutrient uptake. Determining the biomass and nutrient accumulation by cover crops grown in solid-bottom pots within a greenhouse minimizes N leaching losses and allows for more practical harvesting of roots. The objective of this study was to evaluate the effects of cover crop species and fertilizer N rate on the recovery and partitioning of ^{15}N-labeled fertilizer from two different soils by cereal rye and tillage radish cover crops under greenhouse conditions.

MATERIALS AND METHODS

Experimental Design

This study was conducted in a controlled environment greenhouse at the University of Arkansas in Fayetteville, AR in 2016 and arranged in a completely randomized design. Treatments were organized in a three by three full factorial with three N fertilizer rates (0, 34, and 67 kg N ha^{-1}) applied to three cover crop treatments (cereal rye monoculture, tillage radish monoculture, and cereal rye-tillage radish blend). Every treatment combination was replicated three times in in the surface layers of two field soils collected from the University of Arkansas Agricultural Research and Extension Center (AAREC) in Fayetteville, AR and the Vegetable Research Station (VRS) in Kibler, AR. Soil collected from AAREC was classified as a Captina silt loam (Fine-silty, siliceous, active, mesic Typic Fragiudults) (Soil Survey Staff, 2015) and was collected from a field previously fallow for one year. Soil from VRS was classified as a Roxana silt loam (Coarse-silty, mixed, superactive, nonacid, thermic Typic Udifluvents) (Soil Survey Staff, 2015) and originated from a field under fallow conditions for two years prior to this study. Soil from the top 15 cm of each field location was hand-crushed, separated from gravel and plant material using a 1-cm sieve, and homogenized in a cement mixer. To obtain background values of physical and chemical properties of each soil, subsamples were collected from soil after homogenization and analyzed for pH (1:2 soil to water ratio), Mehlich-3 extractable nutrients (P, K, Ca, Mg, and S) (Zhang et al., 2014) with a Spectro Arcos ICP (SPECTRO Analytical Instruments GmbH, Germany), and total N (TN) and total C (TC) by dry combustion (Nelson and Sommers, 1996) using an Elementar varioMax CN analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). Soil particle size distribution was determined using the hydrometer method (Huluka and Miller, 2014), and organic matter content was analyzed using the weight loss on ignition method (Zhang and Wang, 2014). Soils were extracted using a 2 mol L^{-1} KCl solution (Miller and Sonon, 2014) and analyzed for inorganic N using a Skalar autoanalyzer (Breda, The Netherlands). Analyses indicated similar particle size distribution and pH between the soils, but the Captina soil contained nearly 11 times more inorganic N (NH_4-N + NO_3-N) and 1.8 times more TN than the Roxana soil (Table 2-1).

Greenhouse Procedures

Dry homogenized soil was filled into plastic buckets (29-cm diameter) to a volume of 20 L. Cover crops were planted in buckets in March 2016 and thinned 2 wk after planting to two radishes and ten cereal rye plants bucket^{-1} in the respective monocultures and one radish and six cereal rye plants bucket^{-1} in the mixed treatment. Urea labeled with 3.0 atom % ^{15}N (Sigma Aldrich, Miamisburg, OH) was treated with 0.89 g N-(n-butyl) thiophosphoric triamide (NBPT) kg^{-1} urea [Agrotain Ultra (285 g NBPT L^{-1}), Koch Fertilizer LLC., Wichita, KS] and applied to the soil surface at the rates previously mentioned and incorporated via irrigation immediately after thinning. Supplemental fertilizer for macronutrients (other than N) was not applied based on the results from the Mehlich-3 extraction (Table 2-1). Cover crops were grown in a greenhouse maintained at 27°C, did not receive supplemental lighting, and were irrigated with tap water once a wk.

Biomass samples were collected 3 mo after planting, which corresponds to the approximate duration of fall cover crop growth in Arkansas. Whole tillage radishes were pulled from the soil and partitioned into shoots, which consisted of the leaves, and roots, which consisted of the enlarged taproot above and beneath the soil surface. Radish taproots were rinsed with water to remove soil particles. Aboveground cereal rye biomass was collected from both soils by cutting shoots at the soil surface. Belowground cereal rye biomass was collected from the Roxanna soil by passing soil through a 2-mm sieve and washing the remaining roots with water. Dry weight biomass for plant samples was quantified after cover crop residue was dried at 60°C to a consistent mass (10 d) and extrapolated to a scale of kg ha^{-1}. Plant samples were ground to pass through a 1-mm sieve, and dry matter subsamples (0.0054-0.0069 g) were encapsulated in aluminum foil for analysis. Encapsulated subsamples were submitted to the U.C. Davis Stable Isotope Laboratory (Davis, CA) to be analyzed for atom% ^{15}N and total N (TN) content by an elemental analyzer attached to a continuous flow PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK). Atom % ^{15}N and TN contents of plant material were measured in order to distinguish the source of N recovered by the cover crops as fertilizer N or soil N. Fertilizer N recovery was calculated using the following equation adapted from Hauck and Bremner (1976),

$$FN = \frac{TN(c-b)}{a-b} \quad \text{[Eq. 1]}$$

where *FN* is the mass of fertilizer N (kg N ha^{-1}) recovered by the plant portion, *TN* is the mass of total N uptake (kg N ha^{-1}) in the specified biomass portion, *c* is the atom % ^{15}N in the plant portion, *b* is the background atom % ^{15}N calculated from the average atom % ^{15}N in the plants that did not receive N fertilizer, respective to each plant component and cover crop species, and *a* is the atom % ^{15}N of the 15-labelled urea fertilizer. Recovery of soil N (kg N ha^{-1}) was calculated by subtracting the amount of fertilizer N uptake (kg N ha^{-1}) from the TN uptake (kg N ha^{-1}) for each cover crop portion. Fertilizer N recovery efficiency (FNRE) (%) was determined using the equation,

$$FNRE = \frac{FN}{FR}\ x\ 100 \quad \text{[Eq.2]}$$

where FN is the mass of fertilizer N (kg N ha^{-1}) recovered by the plant portion and FR is the application rate of ^{15}N-enriched fertilizer N (kg N ha^{-1}).

Data Analysis

Statistical analyses were conducted using JMP Pro 13 (SAS Inst., 2017). Cover crop biomass accumulation, TN uptake, fertilizer N uptake, FNRE, and soil N uptake were analyzed in a completely randomized design with a three by three factorial treatment structure. The effects of cover crop treatment (cereal rye monoculture, tillage radish monoculture, and cereal rye-tillage radish blend), fertilizer N rate (0, 34, and 67 kg N ha^{-1}), and cover crop by fertilizer N rate were analyzed for each portion of the cover crops (roots, shoots, and total) to examine the partitioning of growth and N uptake. Statistical tests were performed separately for each soil due since root samples were not collected from both soils. Significant means were separated using Student's t pairwise comparison at a significance level of 0.05.

RESULTS AND DISCUSSION

Biomass Accumulation and Partitioning

The total amount of dry matter growth, as well as dry matter partitioned in the shoots and roots, for cover crops grown in the Captina soil were significantly affected by cover crop treatment (Table 2-2). Fertilizer N rate did not influence biomass production for cover crops in the Captina soil (Table 2-2), which could likely be attributed to sufficient residual N in the soil (15.1 mg kg^{-1} inorganic N) at the time of cover crop planting (Table 2-1). When grown in monoculture, radishes produced 1034 kg ha^{-1} of root biomass, which accounted for only 26% of the total radish biomass (Table 2-3). Radishes in monoculture produced 3019 kg ha^{-1} of shoot biomass, nearly twice as much shoot dry matter than cereal rye in monoculture, which reflects inherent growth rate differences between tillage radish and cereal rye in warm conditions. The difference in aboveground dry matter production between cereal rye and tillage radish observed in this study is consistent with that of Kristensen and Thorup-Kristensen (2004) who reported that fodder radish (*Raphanus sativus* L. var. *oleiformus* Pers.) accumulated nearly 4 Mg ha^{-1} of shoot biomass, while cereal rye produced approximately 2 Mg ha^{-1} of shoot biomass after 3 mo. Shoot biomass of cover crops in the radish/cereal rye blend was similar to that of radish in monoculture but greater than that of cereal rye in monoculture, which could indicate that tillage radish shoots grew faster due to warm air temperature (27°C) and outcompeted cereal rye above the soil surface.

The air temperature and duration of this greenhouse experiment resemble fall cover crop growth with early termination in some regions of Arkansas. Results from this study indicate that tillage radish produced more shoot biomass than cereal rye in the Captina soil and reflect that tillage radish, a cold-sensitive crop, produces more growth than cereal rye, a winter-hardy crop, in the fall when ambient temperatures are warmer. Similar results were obtained in a study by Finney et al. (2016), in which the authors observed that dry matter accumulation by tillage radish was 1.6 times greater than cereal rye in the fall. In the same study (Finney et al., 2016), 84% of the total cereal rye growth occurred in the spring, while tillage radish winterkilled and did not accumulate additional dry matter in the spring.

Whole plant and root biomass accumulation were significantly affected by the interaction of cover crop species with fertilizer N rate (Table 2-4). Cereal rye that was grown in monoculture and received the greatest fertilizer N rate (67 kg N ha^{-1}) produced the maximum root biomass with 1167 kg ha^{-1}. Tillage radish in the untreated control accumulated only 276 kg ha^{-1} of root dry matter, which accounted for only 24% of the maximum root biomass accumulation (Table 2-5). Shoot dry matter growth increased with fertilizer N rate, regardless of cover crop treatment. Application rates of 34 and 67 kg N ha^{-1} resulted in incremental shoot biomass increases of 113% and 15% with each increasing fertilizer N rate, respectively (Table 2-5). Cover crops that did not receive fertilizer N produced the least amount of whole plant biomass, which indicates that some additional N in the form of fertilizer might be needed for cover crops grown in N-limited soils, like the Roxanna soil, to facilitate greater biomass production. The majority of biomass production occurred in the shoots, but cover crop shoot biomass did not differ among cover crop treatments. Cereal rye roots accounted for a greater proportion of the respective whole plant biomass than tillage radish roots. The shoot: root biomass ratio varied from approximately 2.5:1 to 3.5:1 in tillage radish and 1.7:1 to 2.0:1 in cereal rye (Table 2-5). Results from a study by Sievers and Cook (2018) showed that cereal rye can produce nearly three times more root biomass than shoot biomass when planted in the fall and terminated in the spring. Planting tillage radish and cereal rye in a blend did not provide advantages in shoot dry matter production over the respective monocultures, suggesting that tillage radish and cereal rye competed for nutrients and light and failed to compensate for decreased seeding rates when blended. Similar observations were made by Finney at al. (2016) who found that total biomass (fall through spring) produced by a mixture of winter-killed (forage radish and oats) and winter-hardy cover crops (canola (*Brassica napus* L.) and cereal rye) was greater than the winter-killed monocultures but less than the winter-hardy monocultures. The authors suggested that shoot biomass of the mixture did not exceed that of the canola or cereal rye monocultures because the winter-killed species outcompeted the winter-hardy species in the fall, and as a result, the winter-hardy species could not compensate in the spring for diminished growth in the fall.

TN Uptake and Partitioning

For cover crops grown in the Captina soil, shoot TN storage accounted for a majority of the whole plant TN uptake. Tillage radish shoots accumulated nearly 84% of the whole plant TN (Table 2-3), which is similar to results from Kanders et al. (2017), who found that 79% of the whole plant TN was distributed in the radish shoots. Total N storage in tillage radish roots averaged 14 kg N ha^{-1} across all cover crop treatments and fertilizer N rates (Table 2-3). Although increasing the supply of available N through added fertilizer N did not increase cover crop biomass in the Captina soil, shoot and whole plant TN uptake increased when fertilizer N was added. Cover crops partitioned on average 55 kg N ha^{-1} of TN in the shoots in the absence of fertilizer N application, but the uptake of TN increased to an average of 79 kg N ha^{-1} when fertilizer N was applied (Table 2-3). Whole plant TN averaged 61 kg N ha^{-1} without fertilizer N and 89 kg N ha^{-1} with the addition of at least 34 kg N ha^{-1} of fertilizer N. Results from this study suggest that TN accumulation by cereal rye and tillage radish shoots is similar despite differences in shoot biomass. These results differ from that of Kristensen and Thorup-Kristensen (2004); the authors observed that fodder radish produced nearly twice as much shoot biomass and accumulated 1.7 times more TN in the shoots than cereal rye after 3 mo. Total N uptake by the whole plant in the cereal rye-tillage radish mixture was similar to that of both monoculture treatments (Table 2-3). Differences in total TN uptake between radish in monoculture and cereal rye in monoculture likely reflect the absence of data for TN partitioning to the cereal rye roots. Similar to biomass partitioning, the majority (86%) of the TN uptake by the radishes in monoculture was partitioned to the shoots in the present study (Table 2-3). While root TN uptake was not influenced by fertilizer N rate, application of N fertilizer increased the average shoot and total TN uptake of cover crops, regardless of cover crop treatment. Total N uptake increased from the untreated control by 44% and 45% in the shoots and whole plant, respectively, when 34 or 67 kg N ha^{-1} of N fertilizer was applied (Table 2-3).

Similar to cover crops in the Captina soil, most of the TN sequestered by cover crops in the Roxanna soil was translocated to the shoots. Shoot TN uptake accounted for 74%, 76%, and 77% of the total TN captured by cover crops receiving 0, 34, and 67 kg N ha^{-1}, respectively. Partitioning of TN to the roots was affected by the interaction between cover crop treatment and fertilizer N rate (Table 2-4). Root TN uptake by cereal rye in monoculture was significantly greater than that of radish roots in monoculture and cover crops in a blend when fertilizer N was applied (Table 2-5). Cereal rye in monoculture that received the highest fertilizer N rate stored the greatest amount of TN in roots, which can be attributed to larger root biomass accumulation than tillage radish (Table 2-5). Shoot and total TN uptake did not differ among cover crop treatments, but each incremental increase in fertilizer N rate resulted in an increase in TN sequestered by the shoots and whole plants. Without added fertilizer N, cover crops in the Roxanna soil accumulated at most 20 kg N ha^{-1} of TN (Table 2-5). Shoot and total TN uptake for all cover crops receiving 34, and 67 kg N ha^{-1} were approximately two and three fold greater, respectively, than cover crops receiving no additional fertilizer N (Table 2-5). As more fertilizer N was added, shoot growth increased and the capacity for N uptake increased accordingly for all cover crops.

Fertilizer N Uptake, Partitioning, and Recovery Efficiency

Overall, a minor portion of the N recovered by cover crops was labelled fertilizer N, and cover crops were surprisingly inefficient in recovering fertilizer N under controlled environmental conditions. The proportion of the TN captured as fertilizer N ranged from 12% in the shoots and whole plants that received 34 kg N ha^{-1} to 22% in the shoots that received 67 kg N ha^{-1} for all cover crops in the Captina soil. Tillage radish roots played a minimal role in storing fertilizer N. On average, 2 kg N ha^{-1} of fertilizer N (7% of applied fertilizer N) was stored in the radish roots, regardless of fertilizer N rate and cover crop treatment (Table 2-6). Fertilizer N accumulation by radish roots accounted for only 22% and 13% of the entire fertilizer N recovery by radishes receiving 34 and 67 kg N ha^{-1}, respectively. While fertilizer N rate did not have a significant effect on the recovery of fertilizer N by radish roots, cover crop shoots and whole plants captured 1.9 and 1.7 times more fertilizer N, respectively, when the N rate increased from 34 kg N ha^{-1} to 67 kg N ha^{-1} (Table 2-6). The maximum mass of fertilizer N recovered by cover crops in the Captina soil was 19 kg N ha^{-1}, and whole plant FNRE was at most 38% (Table 6). The minute mass of fertilizer N applied to each bucket (at most 1.0 ± 0.2 g bucket^{-1}) was likely diluted by the residual inorganic N or N mineralized from organic N, which could account for the low FNRE by cover crops in the Captina soil. The low FNRE by cover crops could also be attributed to substitution of soil N pools with added fertilizer N, which would render the fertilizer N unavailable for plant uptake (Rao et al., 1991). Shoot and root FNRE did not differ significantly among cover crop treatments or fertilizer N rates (Table 2-4), but cover crop shoots were 3.8 times more efficient at recovering applied N than cover crop roots (Table 2-6). Total FNRE of cover crops in monoculture were similar to that of cover crops in the mixed treatment (Table 2-6), which follows the trends observed for TN uptake (Table 2-3). The difference in FNRE observed between tillage radish and cereal rye monocultures is likely due to differences in the biomass collected (whole radishes versus cereal rye shoots).

Similar results for fertilizer N uptake and FNRE were observed for cover crops grown in the Roxanna soil. The mass of fertilizer N recovered in the Roxanna soil did not differ between cover crop species but varied with the amount of fertilizer N applied. A two-fold increase in fertilizer N rate resulted in a proportional two-fold increase in the mass of fertilizer N recovered by cover crops in each plant portion (Table 2-7). The mass of N recovered as labeled fertilizer N by cover crops ranged from 2 to 21 kg N ha^{-1} (Table 2-7). The percent of TN recovery accounted for by fertilizer N uptake ranged from 22% in cover crop roots receiving 34 kg N ha^{-1} to 35% in cover crop shoots receiving 67 kg N ha^{-1}. Much like biomass accumulation and TN uptake, most of the fertilizer N recovered by cover crops was partitioned to the shoots. For cover crops receiving 34 and 67 kg N ha^{-1}, 78% and 79% of the total fertilizer N recovered, respectively, was stored in the shoots (Table 2-7). Whole cover crop plants recovered at most 30% of the applied fertilizer N across all cover crop treatments and N rates (Table 2-7).

Cover crop FNRE for shoots was at least three fold greater than that for cover crop roots (Table 2-7). The FNRE of cover crop shoots in the radish monoculture and radish/cereal rye mixture was 1.3 times greater than that of cereal rye in monoculture, regardless of fertilizer N rate (Table 2-7). Greater root growth and TN stored in cereal rye roots in monoculture when fertilizer N was applied could have contributed to a lower percentage of recovered fertilizer N that was translocated to the cereal rye shoots compared to that of the radish monoculture and radish/cereal rye mix, hence a slightly lower FNRE for cereal rye in monoculture. Additionally, the lower shoot FNRE for cereal rye compared to tillage radish could possibly be attributed to the timing of fertilizer N application, which did not coincide with cereal rye's stage of maximum N demand and uptake in this study. Some studies have shown that the recovery of added fertilizer N can be improved by applying the fertilizer N near the growth stage in which N demand is greatest or by splitting fertilizer N applications. Wuest and Cassman (1992) observed that the FNRE of irrigated wheat for N applied at anthesis was at most 80%, while the FNRE for

N applied at planting was at most 55%. Olson and Swallow (1984) also showed that FNRE is greater for fertilizer N applied to winter wheat in the spring during rapid growth than in the fall.

Soil N Uptake Partitioning

The majority of N recovered by cover crops from both soils was unlabeled soil N, and most of the soil N recovered by cover crops was stored in the shoots. For cover crops grown in the Captina soil, the partitioning of soil N to roots and shoots did not vary among cover crop treatment or fertilizer N rate, but soil N uptake by whole plants differed among cover crop treatment (Table 2-2). Since soil N uptake was calculated as the difference between TN uptake and fertilizer N uptake and fertilizer N uptake was not significantly different among cover crop treatments, the least square means of soil N uptake (data not shown) were similar to that of TN uptake (Table 2-3). Still, the soil N partitioning data reflect that all cover crops translocated an overwhelming majority of the recovered soil N to the shoots. The mass of soil N recovered by cover crops in the Captina soil averaged 71 kg N ha^{-1} in the shoots, which was five times greater than the soil N contained in the cover crop roots. Soil N uptake for whole plants in radish monoculture appeared to be much greater than that for cereal rye in monoculture; however, the total plant soil N uptake values do not account for soil N partitioning to cereal rye roots since underground biomass samples of cereal rye were not collected in the Captina soil. Based on the soil analysis conducted before planting, the Captina soil contained approximately 34 kg N ha^{-1} (15.1 mg kg^{-1}) of residual inorganic N in the top 15 cm (Table 2-1), which is less than the total mass of soil N recovered by cereal rye and tillage radish. Therefore, it can be assumed that the soil N captured by cover crops in excess of the residual inorganic N was mineralized from organic N during the extent of this study. Furthermore, mineralization of organic N was likely not catalyzed by the priming effect of added fertilizer N since soil N uptake was not influenced by fertilizer N rate in the Captina soil.

Soil N uptake by cover crops receiving fertilizer N in the Roxanna soil accounted for at least 64% of the TN uptake. Total soil N uptake for cover crops in the Roxanna soil ranged from 20 to 41 kg N ha^{-1}, and the mass of soil N captured by the cover crops increased as more fertilizer N was added. Partitioned and whole plant soil N sequestration was 1.5 and 2 times greater than the untreated control when 34 and 67 kg N ha^{-1} was applied, respectively (Table 2-8). The positive influence of fertilizer N rate on soil N recovery by cover crops can be attributed to the priming effect induced by the addition of fertilizer N to the soil's inorganic N pool. As reported by Westerman and Kurtz (1973), application of N fertilizer can encourage mineralization of organic N and facilitate the increase in soil N uptake by plants. According to the initial soil test, the Roxanna soil contained approximately 3 kg N ha^{-1} (1.4 mg kg^{-1}) of residual inorganic N in the top 15 cm (Table 2-1). Since the mass of soil N uptake in almost all portions of the cover crops was greater than the amount of residual soil N, it can be assumed that the majority of soil N recovered was mineralized from the organic N pool throughout the growth of the cover crops. Based on the difference in total soil N uptake for cover crops in the control and cover crops that received fertilizer N, the impact of the priming effect, or added nitrogen interaction (ANI) (Rao et al., 1991), ranged from 10 to 21 kg N ha^{-1} in the Roxanna soil. The addition of fertilizer N increased root growth (Table 2-5) for all cover crops, which could have also facilitated greater soil N uptake with increasing fertilizer N rate.

Upon recovery by cover crops, most of the soil N was stored in the shoots. The proportion of whole plant soil N that accumulated in shoots ranged from 74% in cover crops receiving 34 kg N ha^{-1} to 77% in cover crops receiving 67 kg N ha^{-1} (Table 2-8). Recovery and storage of soil N by roots varied with the interaction between cover crop treatment and fertilizer N rate (Table 2-4). Root accumulation of soil N varied from 3 kg N ha^{-1} in tillage radish that did not receive fertilizer N to 13 kg N ha^{-1} in cereal rye that received the most fertilizer N (Table 2-8). The mass of soil N stored in cereal rye roots was significantly greater than that of tillage radish roots when fertilizer N was applied. On average, cereal rye roots sequestered 10 kg N ha^{-1}, which was approximately twice as much as the average soil N stored in tillage radish roots (Table 2-8). The magnitude of increase in soil N storage by cereal rye roots compared to that of tillage radish roots can be attributed to greater root biomass production by cereal rye. For all fertilizer N rates, growing tillage radish and cereal rye in a blend did not improve soil N uptake over that in the monocultures, which could indicate that interspecies competition limited growth and N recovery.

CONCLUSIONS

Under warm greenhouse conditions in the Captina soil, radishes in monoculture accumulated more shoot biomass than cereal rye in monoculture, which reflects that radish produces shoot biomass more rapidly under warmer temperatures than cereal rye. However, the greater biomass production by tillage radish shoots did not result in greater shoot TN uptake by tillage radish compared to cereal rye shoots in the Captina soil. Results from cover crops grown in the Roxanna soil showed that cereal rye can compensate for slow shoot growth in the fall with greater root growth than tillage radish when adequate N is applied (67 kg N ha^{-1} for the Roxanna soil). By producing more root biomass, cereal rye created a larger root sink for TN than tillage radish roots.

The major source of N recovered by cover crops in both soils originated from residual N in the soil at the time of planting or N mineralized from organic N sources. Under controlled conditions that limited N loss due to leaching and ammonia volatilization, cereal rye and tillage radish recovered a greater mass of fertilizer N as the supply of N increased; however, cover crops captured at most 38% of the fertilizer N that was applied. Cereal rye and tillage radish likely attained maximum biomass accumulation under the given environmental conditions and root growth constraints imposed by the enclosed bucket (Poorter et al., 2012). Consequently, N uptake was limited by root and shoot biomass production, and a majority of the applied fertilizer N remained in the soil, resulting in low FNRE values.

Results from this study indicate that N recovery and partitioning by cover crops varies with cover crop species and N availability. Although tillage radish can produce similar or greater amounts of shoot biomass than cereal rye under warm growing conditions, cereal rye can produce more root dry matter than tillage radish and accumulate a greater mass of N belowground before undergoing dormancy. It was also determined that growing tillage radish and cereal rye together in a blend often does not result in increased dry matter production or N acquisition over that of either monoculture, which could likely be attributed to interspecies competition for nutrients and light. Increasing the amount of plant-available N through the application of fertilizer N facilitated greater biomass production by cover crops in the N-limited soil (Roxanna soil) and N recovery by all cover crops regardless of residual N at the time of planting. The positive effect of fertilizer N on the aboveground and belowground dry matter production of cover crops in the soil with low residual N might indicate that application of fertilizer N to cover crops grown in N-limited soils could be advantageous for encouraging cover crop growth and N sequestration. However, the maximum FNRE for cover crops in the N-limited soil reflect that approximately 70% of the applied fertilizer N either remained in the soil following after 3 mo of cover crop growth or was lost via denitrification, volatilization, or immobilization. As a result, the addition of fertilizer N to cover crops in a field would not be advantageous economically or environmentally, unless fertilizer N is required to produce sufficient biomass for the desired goal of cover cropping.

Results from this study of the partitioning of N by cereal rye and tillage radish can provide some insight into the cover crops' roles in nutrient cycling. Overall, cover crop shoots produced more biomass than roots, which resulted in a larger sink for sequestered N. As a result, most of the N sequestered by cover crops would be tied up in the aboveground residue or remain on the soil surface upon cover crop termination and mineralization if cover crop residue is surface applied. Without tillage, aboveground cover crop dry matter would release N more slowly than belowground dry matter due to limited soil contact, which is vital for mineralization by soil microorganisms. Depending on environmental conditions, cover crop species, and the C:N ratio of the residue, aboveground cover crop biomass would likely immobilize more N than belowground dry matter, which could result in greater early-season fertilizer N application for the following cash crop. Nitrogen deposited on the soil surface from cover crop residue could also be prone to loss in a no-till system, especially if the N is not translocated to the root zone of the soil for recovery by the subsequent cash crop. Early termination of cover crops, such as winterkill, can also leave N in aboveground residue vulnerable to loss since N can be readily leached from the frozen or dried residue onto the soil surface (Miller et al., 1994). Therefore, the growth habit, in relation to cold tolerance, and the amount of root dry matter production should be considered when selecting cover crop species for the purpose of capturing and recycling nutrients in a no-till cropping system.

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TABLES

Table 2-1. Physical and chemical properties from the 0- to 15-cm depth of the Captina and Roxanna silt loam soils.

Soil	pH	SOM†	Sand‡	Silt	Clay	TN§	TC§	NO_3-N & NO_2-N ¶	NH_4-N	P#	K	Ca	Mg	S
			g kg^{-1}						mg kg^{-1}					
Captina silt loam	5.3	16	290	600	110	568	6600	12	3	67	226	597	37	11
Roxanna silt loam	6.8	11	280	600	120	303	4814	1	1	70	153	1518	280	4

† Soil organic matter (SOM) analyzed by weight loss on ignition (Zhang and Wang, 2014).

‡ Particle size distribution determined by hydrometer method (Huluka and Miller, 2014).

§ Total nitrogen (TN) and total carbon (TC) determined by dry combustion (Nelson and Sommers, 1996).

¶ Inorganic N (NO_3-N, NO_2-N, and NH_4-N) extracted with 2 mol L^{-1} KCl (Miller and Sonon, 2014) and determined by autoanalyzer.

Phosphorus, potassium, calcium, magnesium, and sulfur extracted with Mehlich-3 solution (1:10 soil to solution ratio) (Zhang et al., 2014).

Table 2-2. Analysis of variance for root, shoot, and total biomass accumulation, total N (TN) uptake, fertilizer N uptake, fertilizer N recovery efficiency (FNRE), and soil N uptake for cover crops in the Captina soil series as influenced by cover crop treatment, fertilizer N rate, and their interaction.

Source	**Root**		**Shoot**		**Total**	
	DF	**Prob > F**	**DF**	**Prob > F**	**DF**	**Prob > F**
		Biomass Accumulation				
Cover Crop	1	0.0083	2	0.0043	2	<0.0001
Fertilizer N Rate	2	0.8817	2	0.0569	2	0.0511
Cover Crop by Fertilizer N Rate	2	0.7469	4	0.6362	4	0.7188
		TN Uptake				
Cover Crop	1	0.1940	2	0.2459	2	0.0301
Fertilizer N Rate	2	0.1276	2	0.0009	2	0.0002
Cover Crop by Fertilizer N Rate	2	0.8885	4	0.4942	4	0.5894
		Fertilizer N Uptake				
Cover Crop	1	0.8714	2	0.6262	2	0.1611
Fertilizer N Rate	1	0.9254	1	<0.0001	1	<0.0001
Cover Crop by Fertilizer N Rate	1	0.8230	2	0.6322	2	0.5948
		FNRE				
Cover Crop	1	0.7817	2	0.2745	2	0.0183
Fertilizer N Rate	1	0.0690	1	0.4876	1	0.1030
Cover Crop by Fertilizer N Rate	1	0.7641	2	0.4836	2	0.3396
		Soil N Uptake				
Cover Crop	1	0.1309	2	0.1924	2	0.0183
Fertilizer N Rate	2	0.3229	2	0.0966	2	0.0510
Cover Crop by Fertilizer N Rate	2	0.8353	4	0.4044	4	0.4615

Table 2-3. Root, shoot, and total biomass accumulation and total N (TN) uptake by cover crops in the Captina soil series as influenced by cover crop treatment and fertilizer N rate.

Main Effect	Root Biomass†‡	Shoot Biomass	Total Biomass	Root TN Uptake§	Shoot TN Uptake§	Total TN Uptake
	——kg ha^{-1}——			——kg N ha^{-1}——		
Cover Crop Treatment						
Tillage Radish	1034 a	3019 a	4053 a	14	71	79 a
Tillage Radish/ Cereal Rye Blend	435 b	2467 a	2902 b			59 ab
Cereal Rye	-	1586 b	1586 c	-		46 b
Fertilizer N Rate						
kg N ha^{-1}						
0	-	-	-		55 b	61 b
34	-	-	-	14	71 a	82 a
67	-	-	-		86 a	96 a

† Values followed by a different lowercase letter are significantly different (P < 0.05) within a column for a given main effect within a soil series.

‡ Root TN uptake was averaged between the tillage radish monoculture and the blend, and shoot TN uptake was averaged for all cover crop treatments due to lack of significant difference.

§ Root, shoot, and total TN uptake values were also averaged across cover crop treatments for each fertilizer N rate in the Captina soil.

Table 2-4. Analysis of variance for root, shoot, and total biomass accumulation, total N (TN) uptake, fertilizer N uptake, fertilizer N recovery efficiency (FNRE), and soil N uptake for cover crops in the Roxanna soil series as influenced by cover crop treatment, fertilizer N rate, and their interaction.

Source	**Root**		**Shoot**		**Total**	
	DF	**Prob > F**	**DF**	**Prob > F**	**DF**	**Prob > F**
Biomass						
Cover Crop	2	0.0485	2	0.8556	2	0.4695
Fertilizer N Rate	2	<0.0001	2	<0.0001	2	<0.0001
Cover Crop by Fertilizer N Rate	4	0.0131	4	0.0895	4	0.0251
TN Uptake						
Cover Crop	2	0.0576	2	0.2198	2	0.7318
Fertilizer N Rate	2	<0.0001	2	<0.0001	2	<0.0001
Cover Crop by Fertilizer N Rate	4	0.0212	4	0.8301	4	0.2938
Fertilizer N Uptake						
Cover Crop	2	0.5618	2	0.1283	2	0.2865
Fertilizer N Rate	1	<0.0001	1	<0.0001	1	<0.0001
Cover Crop by Fertilizer N Rate	2	0.1065	2	0.6398	2	0.5172
FNRE						
Cover Crop	2	0.2760	2	0.0148	2	0.0997
Fertilizer N Rate	1	0.9916	1	0.3967	1	0.4785
Cover Crop by Fertilizer N Rate	2	0.2593	2	0.2321	2	0.2655
Soil N Uptake						
Cover Crop	2	0.0221	2	0.1519	2	0.6779
Fertilizer N Rate	2	0.0001	2	<0.0001	2	<0.0001
Cover Crop by Fertilizer N Rate	4	0.0227	4	0.6249	4	0.1915

Table 2-5. Root, shoot, and total biomass accumulation and total N (TN) uptake by cover crops in the Roxanna soil series as influenced by cover crop treatment and fertilizer N rate.

Cover Crop	Fertilizer N Rate	Root Biomass†	Shoot Biomass‡	Total Biomass	Root TN Uptake	Shoot TN Uptake‡	Total TN Uptake‡
	kg N ha^{-1}	kg ha^{-1}			kg N ha^{-1}		
Tillage Radish		276 e		1116 d	3 e		
Tillage Radish/ Cereal Rye Blend	0	568 cd	826 c	1346 d	7 cd	15 c	20 c
Cereal Rye		461 de		1320 d	6 de		
Tillage Radish		706 bcd		2894 ab	8 cd		
Tillage Radish/ Cereal Rye Blend	34	606 cd	1755 b	2119 c	8 cd	31 b	40 b
Cereal Rye		880 b		2446 bc	14 b		
Tillage Radish		568 cd		2758 ab	9 c		
Tillage Radish/ Cereal Rye Blend	67	752 bc	2016 a	2615 b	14 b	48 a	62 a
Cereal Rye		1167 a		3162 a	18 a		

† Values followed by a different lowercase letter are significantly different ($P < 0.05$) within a column for a given main effect or interaction within a soil series.

‡ Shoot biomass, shoot TN uptake, and total TN uptake values were averaged across N rates for each cover crop treatment in the Roxanna soil.

Table 2-6. Fertilizer N partitioning by cover crops averaged across cover crop treatments for each N rate and fertilizer N recovery efficiency (FNRE) of cover crops averaged across N rates for each cover crop treatment in the Captina soil series.

Main Effect	Root Fertilizer N Uptake†	Shoot Fertilizer N Uptake	Total Fertilizer N Uptake	Root FNRE‡	Shoot FNRE‡	Total FNRE
	kg N ha^{-1}			%		
Cover Crop Treatment						
Tillage Radish	-	-	-	5	26	38 a
Tillage Radish/ Cereal Rye Blend	-	-	-			32 ab
Cereal Rye	-	-	-	-		25 b
Fertilizer N Rate						
kg N ha^{-1}						
34	2	9 b	11 b	-	-	-
67		17 a	19 a	-	-	-

† Means followed by the same lowercase letter are not significantly different ($P < 0.05$) within a column for a given main effect within a soil series.

‡ Root FNRE was averaged between the tillage radish monoculture and the blend, and shoot FNRE was averaged for all cover crop treatments due to lack of significant difference.

Table 2-7. Fertilizer N partitioning by cover crops averaged across cover crop treatments for each N rate and fertilizer N recovery efficiency (FNRE) of cover crops averaged across N rates for each cover crop treatment in the Roxanna soil series.

Main Effect	**Root Fertilizer N Uptake†**	**Shoot Fertilizer N Uptake**	**Total Fertilizer N Uptake**	**Root FNRE‡**	**Shoot FNRE**	**Total FNRE‡**
		kg N ha^{-1}			%	
			Cover Crop Treatment			
Tillage Radish	-	-	-		27 a	
Tillage Radish/ Cereal Rye Blend	-	-	-	7	24 a	31
Cereal Rye	-	-	-		20 b	
			Fertilizer N Rate			
kg N ha^{-1}						
34	2 b	8 b	10 b	-	-	-
67	4 a	11 a	21 a	-	-	-

† Means followed by the same lowercase letter are not significantly different ($P < 0.05$) within a column for a given main effect within a soil series.

‡ Root and Total FNRE were averaged across all cover crop treatments due to lack of significant difference.

Table 2-8. Soil N uptake partitioning by cover crops as affected by cover crop treatment and N rate in the Roxanna soil series.

Cover Crop	Fertilizer N Rate	Root Soil N Uptake†	Shoot Soil N Uptake‡	Total Soil N Uptake‡
	kg N ha^{-1}			
Tillage Radish		3 e		
Tillage Radish/ Cereal Rye Blend	0	7cd	15 c	20 c
Cereal Rye		6 de		
Tillage Radish		6 de		
Tillage Radish/ Cereal Rye Blend	34	6 d	23 b	30 b
Cereal Rye		11 ab		
Tillage Radish		6 d		
Tillage Radish/ Cereal Rye Blend	67	10 bc	31 a	41 a
Cereal Rye		13 a		

† Means followed by the same lowercase letter are not significantly different (P < 0.05) within a column for a given main effect or interaction within a soil series.

‡ Shoot and total soil N uptake values were averaged across N rates for each cover crop treatment in the Roxanna soil series.

CHAPTER 3

Cover Crop Contributions to Early Season Nutrient Recycling in a No-Till Corn System I: Nitrogen

ABSTRACT

Changes in nitrogen (N) flux within a row crop system can result from the implementation of cover crops, which capture and recycle nutrients at varying capacities and rates. Alterations of the N dynamics due to cover crops can have consequences on the growth of the following cash crop, especially if the release of N from cover crop residue is inadequate or not synchronized with cash crop N demand; therefore, it is important to understand the extent to which various cover crop species recover and release N for the subsequent cash crop. This study was conducted to evaluate the sequestration and release of N from tillage radish (*Raphanus sativus*) and cereal rye (*Secale cereale*) cover crops, as well as the influence of N recycling by these cover crops on the early-season growth and N uptake by the following corn (*Zea mays*) crop in a no-till system. Cover crop treatments included tillage radish monoculture, cereal rye monoculture, tillage radish-cereal rye blend, and no cover crop. Urea enriched with ^{15}N was applied to cover crops after planting at four rates (0, 34, 67, and 101 kg N ha^{-1}) to trace the fate of N in the cover crop-corn system and to evaluate the influence of varying amounts of residual N on the biomass production and N recovery by cover crops. Cover crops produced, at most, 6746 kg ha^{-1} of dry matter and recovered 135 kg N ha^{-1} of total N (TN). In the 2014-2015 growing season, cereal rye accumulated more N than tillage radish due to greater biomass production. However, in the 2015-2016 growing season, characterized by warmer temperatures, cereal rye contained less TN than tillage radish but similar amounts of fertilizer N because dry matter production was not different between the cover crops. Cover crops recovered at most 30% of the fertilizer N in the 2014-2015 growing season and 68% of labeled N in the 2015-2016 growing season, which suggests that application of fertilizer N to cover crops was unnecessary on this soil and could exacerbate N loss. Dry matter production and TN uptake by corn at the V6

growth stage was greatest when corn followed tillage radish. Corn following cereal rye generated the least amount of biomass and lowest TN uptake because most of the captured N was retained in the cereal rye residue. Results from this study indicate that corn should be preceded by tillage radish in monoculture or in a blend with cereal rye in order to maximize N recycling early in the growing season.

INTRODUCTION

Cover crops can change the flux of N within a row crop system by scavenging and relinquishing residual soil N. By serving as temporary sinks for N remaining in the soil after cash crop harvest, cover crops diminish N loss due to leaching, erosion, and runoff. Following cover crop termination, the N contained in cover crop residue is released and enters the plant-available pool at varying rates depending on climate, residue composition, and residue management (Cassman and Munns, 1980; Wagger, 1989a, 1989b; Aulakh et al., 1991; Bending et al., 1998; Mullen, 2011). The timing of N release from cover crop residue in relation to the following cash crop's N need can alter the growth and productivity of the following cash crop if N fertilizer plans are not adjusted accordingly (Wagger, 1989b). Therefore, understanding the N recycling efficiency of cover crops in various row crop systems is important in developing a cover crop management strategy that returns maximum benefits to the production system.

The nutrient sequestration capacity of cover crops is largely determined by the growth and dry matter accumulation (Sainju et al., 1998; Isse et al., 1999; Gastal and Lemaire, 2002; Kristensen and Thorup-Kristensen, 2004). Dry matter production, and concurrent nutrient acquisition, by cover crops is a function of several factors, including inherent growth habit and growth rate of the species, environmental growing conditions, length of growing season, and residual nutrient availability (Dabney et al., 2010). Aboveground biomass provides a sink for recovered N, and the amount produced varies among cover crop species. Shipley et al. (1992) observed that cereal rye captured 45% of residual fertilizer N, whereas hairy vetch (*Vicia villosa* Roth) and crimson clover (*Trifolium incarnatum* L.) only sequestered 10 and 8%, respectively; the authors attributed the capacity of residual N sequestration by cereal rye to greater aboveground dry matter production. Results from other studies indicate that belowground growth also contributes significantly to N sequestration. Sainju et al. (1998) showed that minirhizotron root count was positively associated with aboveground dry matter production and N sequestration. A study by Kristensen and Thorup-Kristensen (2004) revealed that tillage radish roots grew twice as deep as cereal rye roots, and therefore, extracted three times more residual NO_3-N than cereal rye.

For winter cover crops, the cold-tolerance of the species plays an important role in the potential biomass accumulation and N retention. Winter-hardy cover crops, such as cereal rye, are able to withstand colder temperatures by undergoing dormancy when temperatures are too low to facilitate growth. Cold-sensitive species like tillage radish, however, are susceptible to tissue damage or winterkill by sub-freezing temperatures which limits dry matter accumulation and nutrient retention (Dean and Weil, 2009). Tillage radish will tolerate cold temperatures to -4°C, below which, tillage radish is prone to injury, and several consecutive days with temperatures less than -4°C can cause tillage radish to die completely (Weil et al., 2009). As a result, biomass accumulation and nutrient acquisition ceases, and nutrients stored in the residue can be prematurely leached. Miller et al. (1994) found that oilseed radish (*Raphanus sativus* (L.) var. oleifera DC Metzg) lost 10% of the captured N (as NO_3-N or NH_4-N) after freezing, while the percent of sequestered N lost from annual ryegrass (*Lolium multiflorum* L.) and red clover (*Trifolium pratense* L.) ranged from 5 to 9%.

Planting and termination timing for cover crops, especially for cold-sensitive species, also plays an important role in governing the amount of N captured by cover crops. For species that are limited by cold winter temperatures, a majority of growth and dry matter accumulation occurs during the fall when temperatures are warmer (Dean and Weil, 2009; Finney et al., 2016); therefore, delays in planting cold-sensitive species can result in decreased biomass and N accumulation (Vos and van der Putten, 1997; Dean and Weil, 2009). However, most of the growth and biomass production occurs in the spring for many winter-hardy species (Dean and Weil, 2009; Finney et al., 2016), so planting of these species can often be delayed without sacrificing biomass accumulation or N recovery. In studies by Dean and Weil (2009) and Finney et al. (2016), tillage radish completed all growth in the fall, while cereal rye accumulated 63 to 88% of total dry matter in the spring following a winter dormant period. Dean and Weil (2009) observed that N uptake in the fall was greater by tillage radish than cereal rye due to greater dry matter production.

After scavenging residual N, cover crops continue to alter the N dynamics of a cash crop system by returning some or all of the captured N to the soil. Selection and management of cover crop species should be centered on the compatibility of the cover crop with the cash crops in terms of N recycling, since the release of N from cover crop residue can affect the growth and N content of the following cash crop (Wagger, 1989b; Kuo and Jellum, 2002; Andraski and Bundy, 2005). In a study by Kuo and Jellum (2002), subsequent corn yield was nearly 5 Mg ha^{-1} lower when planted into grass cover crops (cereal rye and ryegrass) than when following hairy vetch because the amount of N mineralized from the grass cover crop residue was significantly lower than that from hairy vetch. Wagger (1989b) similarly showed that corn grain yield was significantly lower and responded the most to the addition of fertilizer N following cereal rye than crimson clover or hairy vetch due to N retention in the cereal rye residue.

The rate at which N is released and made available to the following crop is governed by the biochemical composition and management of the cover crop residue (Wagger, 1989a, 1989b; Aulakh et al., 1991; Bending et al., 1998; Mullen, 2011). Residues with greater amounts of complex biochemical compounds release N much slower because the complex structures are more difficult to breakdown by microorganisms (Wagger, 1989a; Bending et al., 1998; Mullen, 2011). Wagger (1989a) observed that cereal rye contained nearly two and three times more cellulose and hemicellulose, respectively, than legume cover crops (crimson clover and hairy vetch) on average throughout the growing season, and the contents of the compounds increased as cover crops developed. Consequently, available N released from cereal rye residue was 3 to 4 times less, on average, than that from legume residue 16 wk after cover crop termination. Furthermore, the C:N ratio of the cover crop residue largely determines whether N is mineralized into plant-available forms or rendered temporarily unavailable through immobilization. Plant residue with low C:N ratios (approximately <20:1) result in net mineralization, while net immobilization occurs when residues with high C:N ratios (approximately >30:1) are added to the soil (Wagger, 1989a; Aulakh et al., 1991; Mullen, 2011). The C:N ratio generally increases as plants mature, and legume and *Brassica* cover crop species typically contain low C:N ratios, while grass species usually contain high C:N ratios (Wagger, 1989a; Clark et al., 1997). Hence, grass cover crops and cover crops terminated at later growth stages will release available N slower than legume and *Brassica* species and cover crops killed earlier, respectively (Clark et al., 1997).

The management of cover crop residue determines the amount of contact with the soil and subsequently, the rate at which residue decomposes and releases available N. Incorporating cover crop residue into the soil through tillage before cash crop planting aerates the soil, physically breaks apart residue, and provides maximum residue-to-soil contact which increases mineralization (Aulakh et al., 1991; Henriksen and Breland, 2002; Mullen, 2011). Unfortunately, repeated tillage over time destroys soil structure, decreases organic matter, and promotes erosion (Martin and Cassel, 1992; Mazzoncini et al., 2011). No-till or minimum-till management is often the recommended practice in regards to cover crop residue management since limiting the disturbance of the soil can minimize erosion loss and prevent organic matter degradation (Karlen et al., 1994; Mazzoncini et al., 2011). Consequently, degradation and N release is slower when residue is left on the surface since direct contact with the soil is limited (Aulakh et al., 1991; Vaughan and Evanylo, 1998).

Investigating the magnitude of N captured and rate of N release by cover crops is important in order to understand the potential impact of cover crops on the following cash crop. As more producers transition to no-till systems for organic matter and soil stabilization benefits, understanding how N is recycled from minimally disturbed cover crop residue is also needed. Although many studies in the Midwest and Mid-Atlantic regions of the U.S. have examined the impact of nutrient recycling by cover crops on overall cash crop productivity, the effect of cover crop N turnover on early-season corn productivity in Mid-South systems has been unreported to this date. Therefore, this study was established to evaluate 1) the capacity and efficiency of N recovery by cereal rye and tillage radish cover crops and 2) the impact of N recycling by cereal rye and tillage radish cover crops on the early-season dry matter production and N uptake by the following corn in a no-till system.

MATERIALS AND METHODS

Experimental Design

This study was arranged in a randomized complete block design with four replications. The experiment consisted of a four by four treatment structure with four cover crop treatments (tillage radish, cereal rye, tillage radish/cereal rye blend, and fallow) and four randomly arranged fertilizer N rates (0, 34, 67, and 101 kg N ha^{-1}). Microplots measuring 1.5 m by 3 m were established in the fall of 2014 and 2015 at the Vegetable Research Station, Kibler, Arkansas (35°22'44.7"N, 94°13'56.9"W) on soil classified as a Roxanna silt loam (Coarse-silty, mixed, superactive, nonacid, thermic Typic Udifluvents) (Soil Survey Staff, 2015). The site used in this experiment was fallow for one year before establishment of this study.

Field Methods

Before cover crop planting, preliminary samples were collected from the top 15 cm of the soil, oven-dried at 60°C to a constant weight, and ground to pass through a 2-mm sieve. Soil samples were analyzed for pH (1:2 soil to water ratio), total N (TN) and total C (TC) using automated dry combustion (Nelson and Sommers, 1996) with an Elementar varioMax CN analyzer (Elementar Analysensysteme GmbH, Hanau, Germany), inorganic N (NO_3-N, NO_2-N, and NH_4-N) using a 2 mol L^{-1} KCl solution extraction (Miller and Sonon, 2014) and a Skalar autoanalyzer (Breda, The Netherlands), and Mehlich-3 extractable nutrients (P, K, and Zn) (Zhang et al., 2014) with a Spectro Arcos ICP (SPECTRO Analytical Instruments GmbH, Germany). Results from the initial soil analyses revealed that the soil at this site had an average pH of 7.3, 605 mg TN kg^{-1}, 4583 mg TC kg^{-1}, 18.7 mg inorganic N kg^{-1}, 72 mg P kg^{-1}, 130 mg K kg^{-1}, and 4 mg Zn kg^{-1}.

Cover crops were planted on 24 September 2014 and 23 September 2015 in rows spaced 23 cm apart using a no-till drill (Hege 1000 series, Wintersteiger Seedmech, Ried im Innkreis, Austria). Tillage radish was seeded at rates of 10 and 5 kg ha^{-1} in the monoculture and tillage radish/cereal rye blend treatments, respectively, and cereal rye was seeded at rates of 103 and 52 kg ha^{-1} in the monoculture and tillage radish/cereal rye blend treatments, respectively. Urea (460 g N kg^{-1}) enriched with ^{15}N (2.4 atom % in 2014 and 3.0% in 2015) (Sigma Aldrich, Miamisburg, OH) and treated at a rate of 0.89 g N-(n-butyl) thiophosphoric triamide (NBPT) kg^{-1} urea [Agrotain Ultra (285 g NBPT L^{-1}), Koch Fertilizer LLC., Wichita, KS] was applied at the aforementioned N rates on 8 October 2014 and 30 September 2015. Cover crops were irrigated as needed using an overhead linear sprinkler irrigation system for optimum stand establishment and incorporation of ^{15}N. On 31 March 2015 and 26 February 2016, cover crop biomass samples were taken from one half of each plot in 91 cm long sections of the middle four rows (0.84 m^2 area). Whole tillage radish plants (leaves + enlarged taproot) were collected by pulling or digging as much of the enlarged taproot as possible. Aboveground cereal rye samples were collected by cutting cereal rye shoots at the soil surface. In the 2015-2016 growing season, aboveground biomass samples of native weeds (henbit (*Lamium amplexicaule*) and annual bluegrass (*Poa annua*)) were also acquired from 0.84 m^2 sections in one-half of each of the fallow plots. The remaining cover crops were terminated using 0.8 kg a.e. ha^{-1} glyphosate (N-(phosphonomethyl) glycine) on 1 April 2015. In the second year of the study, glyphosate was applied on 29 February 2016, and a following application of 0.5 kg a.i. ha^{-1} of paraquat (1,1´-dimethyl-4,4´-bipyridinium ion) was necessary to terminate the remaining cover crops. On 21 March 2016 cover crops were rolled to ensure complete termination of the tillage radish and to provide adequate planting conditions for corn the following week. Although the duration of cover crop growth before sampling was nearly 1 mo shorter in the 2015-2016 growing season than in 2014-2015, warmer winter temperatures in the 2015-2016 growing season of the study allowed cover crops to more rapidly accumulate similar growing degree days as the amount accumulated by cover crops in the first year (Fig. 3-1).

Corn (var. Pioneer 1319HR (Pioneer Hi-Bred International, Johnston, IA)) was planted at a rate of 87,000 seeds ha^{-1} in a flat seedbed approximately 4 wk after cover crop termination on 30 April 2015 and 29 March 2016 directly into cover crop residue in two rows per plot that were spaced 91 cm apart using a no-till drill (Hege 1000 series, Wintersteiger Seedmech, Ried im Innkreis, Austria). Fertilizer was not applied to corn to ensure that N recovered by corn originated from the soil, ^{15}N fertilizer applied to cover crops, or mineralized from cover crop residue. An overhead linear sprinkler irrigation system was used as needed for corn irrigation. Corn was sampled when a majority of the plants reached the V6 stage (11 June 2015 and 16 May 2016) to estimate the impacts of cover crop nutrient recycling on early-season corn nutrition prior to the recommended N fertilizer application at the V6 growth stage. Aboveground corn plant tissue was collected in a 91-cm section of both rows (1.65 m^2 area) from the half of each plot in which cover crop biomass samples were not taken. Corn planted into cereal rye residue in 2016 failed to achieve plant stands sufficient for sampling, so corn biomass and nutrient uptake data were not collected from cereal rye plots in 2016.

Cover crop and corn tissue samples were oven-dried for 10 d at 60°C and weighed. Dry matter weight and sampling area were used to calculate the biomass produced by the cover crops and corn. Plant samples were ground to pass through a 2-mm sieve, weighed into tin capsules, and submitted to the U.C. Davis Stable Isotope Laboratory (Davis, CA) for ^{15}N and TN analysis using an elemental analyzer with a continuous flow PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK). The TN and ^{15}N data for cover crops and corn were used in the following equation (adapted from Hauck and Bremner (1976)) to calculate the amount of fertilizer N recovered by cover crops and corn,

$$FN = \frac{(TN)(c-b)}{a} \quad [1]$$

in which *FN* is the mass of fertilizer N uptake (kg N ha^{-1}), *TN* is the mass of total N recovered (kg N ha^{-1}), *c* is the atom % ^{15}N analyzed by the isotope ratio mass spectrometer, *b* is the average background atom % ^{15}N obtained from the atom % ^{15}N of the plants that were not fertilized with ^{15}N-enriched urea, and *a* is the atom % ^{15}N of the fertilizer source. The mass of soil N (kg N ha^{-1}) acquired by cover crops and corn was determined as the remaining portion of recovered TN that was not labeled fertilizer N. Fertilizer N recovery efficiency (FNRE) (%) was calculated by dividing the respective fertilizer N rate (kg N ha^{-1}) applied to the cover crops by the mass of fertilizer N recovered by the cover crops or corn (kg N ha^{-1}) and converting to percent.

The mass of fertilizer N remaining in the soil at cover crop termination in each growing season was approximated at four 15-cm incremental depths (0 to 15, 15 to 30, 30 to 45, and 45 to 60 cm). Soil samples were collected the same day cover crop biomass samples were obtained from every plot in the 2014-2015 growing season, but in the 2015-2016 growing season, soil samples were collected only from the plots receiving 0 or 101 kg N ha^{-1} of fertilizer N. Samples were oven dried at 40°C and ground to pass through a 2-mm sieve. Subsamples weighing 76 ± 4 mg were encapsulated in tin foil and submitted to the U.C. Davis Stable Isotope Laboratory to be analyzed for TN and ^{15}N content. The amount of fertilizer N (kg N ha^{-1}) in each interval depth was calculated using the equation above, assuming a constant bulk density of 1.35 g cm^{-3} for comparison purposes.

Data Analysis

Data were analyzed using JMP Pro 13 using a mixed model with cover crop, fertilizer N rate, and cover crop by fertilizer N rate as fixed effects and replication as a random effect. Response variables were analyzed by growing season since the number of samples varied between years. Soil ^{15}N data were also analyzed by depth increment for each growing season. Significant means were separated using Student's T pairwise comparison and a significance level of 0.05.

RESULTS AND DISCUSSION

Weather Conditions

The 2014-2015 and 2015-2016 growing seasons were characterized by different ambient temperatures that influenced cover crop growth. During the period of cover crop growth (planting to sampling/termination), daily minimum temperatures were nearly 2°C lower and daily maximum temperatures were nearly 3°C lower, on average, in the 2014-2015 growing season than those in the 2015-2016 growing season (Table 3-1). The 2014-2015 growing season experienced over three times more minimum daily temperatures below -4°C than the 2015-2016 growing season, which contributed to winterkill of many tillage radishes in 2014-2015 (Table 3-1). Tillage radishes likely winterkilled in the first week of January 2015 since 26 d in this time period had low temperatures below -4°C (Weil et al., 2009). Winterkill and premature decomposition of tillage radish prevented complete collection of some tillage radishes, and likely led to underestimation of the potential dry matter production and nutrient content of tillage radish in the 2014-2015 growing season. Warmer temperatures during the cover crop growing period in the 2015-2016 growing season facilitated faster growth and growing degree accumulation by cover crops than the 2014-2015 growing season (Fig. 3-1), so cover crop biomass samples were collected earlier in 2015-2016. During the periods of cover crop desiccation (between cover crop sampling/termination and corn planting) and corn growth (corn planting to corn sampling at V6 stage), mean daily temperatures were, on average, 3°C warmer in the 2014-2015 growing season than the 2015-2016 growing season, and temperatures below -4°C were not reported (Table 3-1). The warmer growing conditions for corn in the 2014-2015 growing season is likely attributable to later planting date for corn (approximately 4 wk).

Cover Crop Biomass Accumulation

The mass of dry matter produced by cover crops varied with the interaction of cover crop species and the rate of fertilizer N applied in both growing seasons (Tables 3-2, 3-3). Application of 101 kg N ha^{-1} to cereal rye in monoculture resulted in the highest cover crop biomass production, while application of 101 kg N ha^{-1} to tillage radish in monoculture resulted in the lowest biomass production for cover crops in the 2014-2015 growing season (Table 3-4). Biomass accumulation by cereal rye in monoculture and cover crops in the blend ranged from 3842 to 6350 kg ha^{-1} and 3996 to 4750 kg ha^{-1}, respectively. White and Weil (2011) observed comparable average dry matter accumulation by cereal rye (3821 kg ha^{-1}) over a similar duration of time. Treatments that contained cereal rye produced significantly more dry matter as the rate of fertilizer N increased. Dry matter accumulation for tillage radish in monoculture did not significantly increase with fertilizer N rate in 2014-2015 (Table 3-4). Each fertilizer N application rate within the cereal rye monoculture resulted in a significant increase in biomass production relative to the non-fertilized cereal rye in monoculture, whereas, the only significant increase in cover crop dry matter production within the blend occurred when the maximum fertilizer N rate was applied (Table 3-4).

Differences in cold tolerance between tillage radish and cereal rye were reflected in the cover crop biomass results in the 2014-2015 growing season. Cereal rye in monoculture and cover crops in the tillage radish-cereal rye blend, on average, produced three times more dry matter than tillage radish in monoculture (Table 3-4), which can be attributed to cereal rye's ability to withstand colder temperatures by undergoing dormancy and resuming growth in late winter/early spring. Many of the tillage radishes, especially in the higher fertilizer N rate treatments, winterkilled and began to undergo decomposition prior to sampling in the first year of the study, which limited growth and complete collection of biomass samples. Consequently, tillage radish total dry matter accumulation averaged 1106 kg ha^{-1}, which is less than the average tillage radish dry matter of 4139 kg ha^{-1} observed by White and Weil (2011) within approximately 3 mo of growth when planted in August. More vigorous growth under colder temperatures in the 2014-2015 growing season also allowed cereal rye to outcompete tillage radish and account for 85%, on average, of the total cover crop biomass in the blend (data not shown). Therefore, some of the similarities in cover crop biomass accumulation between the tillage radish-cereal rye blend and the cereal rye monoculture can likely be attributed to the majority of the blend comprised of cereal rye biomass.

In the 2015-2016 growing season of the study, cover crops in the blend that received 34 kg N ha^{-1} of fertilizer N produced the greatest amount of dry matter (6746 kg ha^{-1}), while native weeds in the fallow treatment that did not receive fertilizer produced the least (1414 kg ha^{-1}) (Table 3-4). Dry matter accumulation averaged 5970, 6132, and 5720 kg ha^{-1} for tillage radish, the blend, and cereal rye, respectively. The mass of tillage radish dry matter quantified is greater than that (3034 kg ha^{-1}) observed by Dean and Weil (2009) in a study conducted in the Mid-Atlantic region of the US; however, cereal rye produced more biomass (7040 kg N ha^{-1}) in the study by Dean and Weil (2009) than cereal rye in this study. Across cover crop by fertilizer N rate interactions, biomass production by planted cover crops was generally similar, but all established cover crops produced significantly greater biomass than the native weeds in the fallow treatments (Table 3-4). Dry matter production by native weeds in the fallow treatment was significantly greater for those that received 101 kg N ha^{-1} than for the fallow plots that were not fertilized (Table 3-4). Within each established cover crop treatment, the addition of fertilizer N did not result in significant changes in cover crop biomass production compared to the respective non-fertilized treatments; however, trends in dry matter production due to the application of fertilizer N within each cover crop treatment were similar to those in the first season (Table 3-4). In the 2015-2016 season, the magnitude of biomass produced by tillage radish in monoculture tended to decrease (not significantly at $P<0.05$) as the rate of fertilizer N increased, while dry matter production by cereal rye in monoculture tended to increase (not significantly at $P<0.05$) as more fertilizer N was applied (Table 3-4). In the blend, which was dominated by tillage radish dry matter (82%), the highest fertilizer N rate resulted in a significant decrease in biomass production compared to the intermediate fertilizer N rates (34 and 67 kg N ha^{-1}) (Table 3-4). The lack of positive response in tillage radish biomass to fertilizer N application in both growing seasons suggests that the addition of fertilizer N was not necessary to maximize dry matter production for tillage radish on this site. Conversely, application of fertilizer N to cereal rye, especially under cooler growing seasons, might be needed on this site to insure maximum biomass accumulation for cereal rye. Still, N response studies are necessary to determine a recommended fertilizer N rate for each cover crop species relevant to Mid-South climate and production systems.

Cover Crop Total N Uptake

Total N recovery by cover crops in the 2014-2015 growing season differed significantly among cover crop by fertilizer N rate interactions (Tables 3-2, 3-3) and followed trends similar to that of cover crop biomass accumulation. The association between dry matter accumulation and N uptake reported in this study mirrors a similar association observed by Sainju et al. (1998) and Kristensen and Thorup-Kristensen (2004). Across all fertilizer N rates, TN accumulation was significantly greater for cover crops in the blend and cereal rye in monoculture than for tillage radish in monoculture (Table 3-5). Cereal rye in monoculture that received the highest fertilizer N rate (101 kg N ha^{-1}) recovered the greatest mass of TN (117 kg ha^{-1}), while the highest fertilizer N rate applied to tillage radish in monoculture resulted in the lowest TN uptake in the 2014-2015 growing season (Table 3-5). On average, tillage radish recovered 33 kg TN ha^{-1}, which is less than the 119 kg TN ha^{-1} recovered by tillage radish in a study by Dean and Weil (2009). As with dry matter production, fertilizer N application did not significantly affect the mass of TN recovered by tillage radish in monoculture, which indicates that tillage radish planted in monoculture on this site maximized TN uptake without additional fertilizer N. Within the blend, TN uptake tended to increase with fertilizer N rate, and the highest fertilizer N rate resulted in 28% more TN recovered by cover crops compared to the 34 kg N ha^{-1} rate (Table 3-5). Total N uptake by cereal rye ranged from 64 to 117 kg N ha^{-1}, which is slightly lower than the 144 kg TN ha^{-1} observed by Dean and Weil (2009). The mass of TN recovered by cereal rye in monoculture increased with each application of fertilizer N up to the 67 kg N ha^{-1} rate, and TN sequestration by cereal rye that received fertilizer N ranged from 28 to 83% greater than that of cereal rye that did not receive additional N (Table 3-5).

Recovery of TN by cover crops in the 2015-2016 growing season was influenced by the main effects of cover crop treatment and fertilizer N rate (Tables 3-2, 3-3). When averaged across fertilizer N rates, TN uptake by cover crops in the 2015-2016 growing season ranged from 8.5 kg N to 135.3 kg N ha^{-1} (Table 3-5). Planted cover crops recovered at least 11 times more TN than native weeds, which reiterates the advantage of established and managed cover crops over fallow weeds in the sequestration of residual N (Table 3-5). Tillage radish captured 135 kg TN ha^{-1}, which is similar to the 144 kg N ha^{-1} of TN uptake by tillage radish observed by Gieske et al. (2016). Cover crops in blend recovered similar masses of TN compared to the tillage radish monoculture and a significantly greater amount of TN than cereal rye in monoculture (Table 3-5), which reflects that the majority of the blend was comprised of tillage radish in the warmer growing season. When averaged across cover crop treatments, maximum TN uptake occurred when cover crops received 67 kg N ha^{-1} (Table 3-5). Cover crops that did not receive fertilizer N sequestered 91 kg N ha^{-1} of TN, on average, which was not significantly different than the mass of TN accumulated by cover crops that received 34 or 101 kg N ha^{-1} (Table 3-5).

Cover Crop Fertilizer N Uptake and Recovery Efficiency

The mass of fertilizer N recovered by cover crops varied among cover crop by fertilizer N rate interactions in the 2014-2015 growing season (Tables 3-2, 3-3). Tillage radish in monoculture that received the lowest fertilizer N rate (34 kg N ha^{-1}) recovered the least amount of fertilizer N (3 kg N ha^{-1}), while cereal rye in monoculture to which the highest fertilizer N rate was applied accumulated the greatest amount of fertilizer N (32 kg N ha^{-1}) (Table 3-5). Cover crops in the blend and cereal rye monoculture that received at least 67 kg N ha^{-1} of fertilizer N captured at least four and eight times more fertilizer N, respectively, than tillage radish in monoculture (Table 3-5), which is due to greater biomass accumulation. Ranells and Wagger

(1997) similarly showed that cereal rye accumulated four times more ^{15}N fertilizer than crimson clover due to a ten-fold difference in dry matter production. Within the blend and cereal rye monocultures, fertilizer N uptake increased significantly with each incremental increase in fertilizer N rate (Table 3-5). Fertilizer N recovery by tillage radish in monoculture, however, was not significantly influenced by fertilizer N rate (Table 3-5), which is likely due to the lack in growth response to the addition of fertilizer N and winterkill of tillage radish.

The efficiency at which cover crops recovered the applied fertilizer N varied among cover crop treatments in both growing seasons (Tables 3-2, 3-3). In the 2014-2015 growing season, the FNRE of cover crops ranged from 9.6 to 29.6%, and cereal rye in monoculture was at least twice as efficient, on average, in recovering labeled N as tillage radish in monoculture and cover crops in the blend (Table 3-6). Similar results were shown in a study by Ranells and Wagger (1997), in which cereal rye recovered 39% of the applied fertilizer N. Minimal biomass production and growth by tillage radish likely restricted the mass and efficiency by which tillage radish sequestered fertilizer N. Furthermore, winterkill of tillage radish followed by leaching of nutrients from the residue prior to sample collection could have limited the retention of N and, therefore, the mass and efficiency of fertilizer N quantified in the tissue. Cereal rye in monoculture was the most efficient in recovering labeled N in the 2014-2015 growing season (Table 3-6), which could likely be attributed to greater dry matter production and little, if any, loss of captured fertilizer N from tissue prior to sampling. Based on the mean FNRE values for cover crops in the 2014-2015 growing season, greater than two-thirds of the applied fertilizer N was not recovered by the cover crops (Table 3-6). Since the ^{15}N-enriched urea was coated with a urease inhibitor and incorporated by irrigation within 4 d of application, it can be assumed that the amount of fertilizer N lost through ammonia volatilization was minimal. Upon entering the soil, the labeled N could have been leached below the root zone of the young cover crops before extensive root growth could be achieved, which could have limited the recovery of fertilizer N.

The remaining fertilizer N in the soil at cover crop termination in the 2014-2015 growing season was not significantly different among cover crop treatments at each depth interval but varied with the rate of fertilizer N applied to cover crops (Table 3-7). Although most of the cover crops recovered greater amounts of fertilizer N as the rate of applied N increased, the mass of fertilizer N left in the soil after cover crop burndown also increased with fertilizer N rate within each interval soil depth (Table 8). The mass of fertilizer N in the upper three depths was greatest in soils to which 101 kg N ha^{-1} was applied and least in soils that received 34 kg N ha^{-1} (Table 3-8). Residual fertilizer N ranged from 8 to 17 kg N ha^{-1} in the 0 to 15 cm depth, 1 to 4 kg N ha^{-1} in the 15 to 30-cm depth, and 0 to 2 kg N ha^{-1} in the 30 to 45-cm depth (Table 3-8). The mass of fertilizer N in the 45 to 60-cm depth also tended to increase as the fertilizer N rate increased (data not shown), but cover crop by fertilizer N rate also influenced the amount of residual fertilizer N in the lower depth (Table 3-7). Soil under cereal rye that received 34 kg N ha^{-1} contained one of the lowest amounts of fertilizer N (0 kg N ha^{-1}), while soil under no cover crop to which 101 kg N ha^{-1} was applied contained the greatest amount of labeled N (6 kg N ha^{-1}) (Table 3-8). The significant increase in fertilizer N at the lower depth of soil without a cover crop compared to soil with cover crops indicates that soils left fallow over the winter can be more susceptible to leaching of residual N, especially when more N is available.

In the 2015-2016 growing season, the mass of fertilizer N sequestered by cover crops was contingent on the cover crop treatment and the rate of fertilizer N applied (Table 3-3). When averaged across fertilizer N rates, the amount of fertilizer N recovered by cover crops ranged from 5 to 23 kg N ha^{-1} and was maximized by cover crops in the blend (Table 3-5). Although all established cover crops accumulated significantly greater biomass and TN than native weeds in fallow treatments, established cover crops only recovered significantly greater fertilizer N than the native weeds when planted together in a blend (Table 3-5). As expected, fertilizer N uptake by cover crops increased significantly with each incremental increase in fertilizer N rate when averaged across cover crop treatments (Table 3-5). Even though the highest rate (101 kg N ha^{-1}) of fertilizer N did not maximize biomass or TN accumulation by cover crops in the 2015-2016 growing season, the highest fertilizer N rate maximized the accumulation of the labeled N by cover crops (Table 3-5).

At least 15% and at most 68% of the applied fertilizer N was recovered by cover crops in the 2015-2016 growing season (Table 3-6). Native weeds in the fallow plots were the least efficient at capturing labeled N (Table 3-6), which is likely the result of limited growth and biomass accumulation. Cover crops in the blend were the most efficient at recovering fertilizer N and had greater FNRE values, on average, than the cover crop monocultures (Table 3-6). The amount of biomass significantly affected the mass of residual fertilizer N in the lower two soil depths at the time of cover crop burndown (Table 3-7). The amount of labeled N remaining in the upper two soil depths was similar among cover crop treatments and averaged 27 kg N ha^{-1} in the 0- to 15-cm depth and 4 kg N ha^{-1} in the 15- to 30-cm depth (Fig. 3-2). These observations are similar to those of Kristensen and Thorup-Kristensen (2004) in which the amount of $^{15}NO_3$-N remaining in the top 50 cm of soil under tillage radish was similar to that under cereal rye; however, the authors also determined that soils under cereal rye contained more $^{15}NO_3$ than those under tillage radish in deeper (1 to 2.5 m) layers. Soil in which cover crops were planted contained 1 kg N ha^{-1} of fertilizer N on average in the 30- to 45- and 45- to 60-cm depths, and soil without cover crops contained 19 times more labeled N, on average, in each of the lower two soil depths than soils with cover crops (Fig. 3-2). The lower amounts of fertilizer N found in the lower depths of soil under cover crops than soil without cover crops could be attributed to significantly greater biomass production and fertilizer N recovery by established cover crops compared to native weeds in fallow soil. Similar to the 2014-2015 growing season, the significantly greater masses of fertilizer N remaining in the lower depths of the fallow soils indicates that fallow soils are more prone to leaching of residual N than those that contain established cover crops, even if native weeds are present.

Cover Crop Soil N Uptake

The majority of N recovered by cover crops in both growing seasons was non-labeled soil N. In the 2014-2015 growing season, the mass of soil N uptake ranged from 34 to 64 kg N ha^{-1} and varied with cover crop species (Table 3-5). Cereal rye in monoculture and cover crops in the blend, which was dominated by cereal rye biomass, accumulated significantly greater quantities of soil N than tillage radish in monoculture (Table 3-5). Similar to the results observed for TN and fertilizer N uptake, soil N recovery by tillage radish was restricted in the 2014-2015 growing season by cold temperatures that resulted in slowed growth, winterkill before sampling, and limited dry matter accumulation.

Cover crop acquisition of soil N in the 2015-2016 growing season was influenced by cover crop species and the rate of fertilizer N applied to cover crops (Table 3-3). When averaged across fertilizer N rates, the least square means of soil N uptake for each cover crop species was identical to the mass of TN recovered in each cover crop treatment (Table 3-5). Nevertheless, the trends observed in soil N uptake by cover crops was similar to that of TN and fertilizer N uptake. Native weeds in the fallow treatment recovered the least amount of soil N (Table 3-5), which can be explained by the limited mass of dry matter produced by the native weeds. Tillage radish in monoculture and cover crops in the blend, which was dominated by tillage radish biomass, captured the greatest mass of soil N (129 kg N ha^{-1}) (Table 3-5). Although cereal rye in monoculture sequestered the greatest amount of soil N in the first, colder growing season, warmer conditions in the 2015-2016 growing season likely contributed to slower fall cereal rye growth and, subsequently, reduced uptake of residual soil N when compared to tillage radish in monoculture and the blend.

When averaged across cover crop treatments, the amount of soil N captured in cover crop residue ranged from 66 to 91 kg N ha^{-1} in the 2015-2016 growing season (Table 3-5). The mass of soil N recovered by cover crops showed a decreasing trend as the rate of fertilizer N increased; however, the only statistically significant decrease in soil N accumulation occurred when cover crops received the greatest amount of fertilizer N (101 kg N ha^{-1}) (Table 3-5). The percent of TN recovered by cover crops that was residual soil N decreased as more fertilizer N was applied (Table 3-5). When cover crops received 34 kg N ha^{-1} of fertilizer N, 85% of the captured TN in the cover crop residue was soil N, whereas, only 64% of the TN recovered by cover crops was soil N when 101 kg N ha^{-1} of fertilizer N was applied (Table 3-5). The negative relationship between soil N uptake and fertilizer N rate that was observed in the 2015-2016 growing season can be explained by the positive relationship between fertilizer N uptake and fertilizer N rate; as the amount of applied fertilizer N increased, the amount of readily-available fertilizer N accumulated by cover crops increased.

Corn Biomass Accumulation

The cover crop significantly affected the amount of dry matter produced by corn at the V6 growth stage in both growing seasons (Tables 3-2, 3-3). In the first season of the study, corn dry matter production by the V6 growth stage ranged from 53 to 1090 kg ha^{-1} (Table 3-4). When planted into tillage radish residue, corn produced significantly more biomass than corn planted into the blend, cereal rye, or soil without cover crops (Table 3-4). Much of the tillage radish residue decomposed prior to corn sampling at the V6 stage, which could indicate that some of the nutrients captured by the tillage radish residue were released and made available to the corn by the time the corn was sampled. Corn dry matter production significantly decreased when planted into cereal rye residue compared to the other cover crop and fallow treatments (Table 3-4). Cereal rye residue contributed to a 20-fold decrease in corn biomass accumulation compared to tillage radish residue and a five-fold decrease, on average, compared to the cover crop blend and no cover crops. At the corn biomass sampling time near the V6 growth stage, most of the cereal rye residue remained intact and standing almost upright within the plots, signifying that minimal decomposition, if any, had occurred. Consequently, most of the captured nutrients likely remained in the residue and unavailable to the corn, which could explain the decreased growth observed in corn planted after cereal rye. Corn planted into the tillage radish-cereal rye blend residue produced similar amounts of dry matter compared to corn planted into fallow soil but more than corn following cereal rye (Table 3-4). The rapid decomposition of tillage radish residue and subsequent nutrient release to the next corn crop could have compensated for a portion of the nutrients withheld in the cereal rye residue within the blend.

In the 2015-2016 growing season, corn accumulated 179 to 584 kg ha^{-1} of biomass (Table 3-4). Corn produced maximum dry matter when planted after tillage radish (Table 3-4), which likely resulted from rapid decomposition and release of nutrients from tillage radish residue. Unlike the 2014-2015 growing season, corn planted into the blend residue produced twice as much aboveground growth than corn planted into fallow (Table 3-4). Since tillage radish dominated the cereal rye/tillage radish blend in the warmer fall growing season and TN recovery was significantly greater by cover crops in the blend than by native weeds in the fallow treatments, cover crops in the blend had the potential to return a greater amount of nutrients to the soil than native weeds early in the corn growing season. Thus, biomass accumulation by corn planted into fallow was likely diminished by limited available soil nutrients recycled by the native weeds.

Corn Total N Uptake

The amount of TN amassed by corn varied similarly by the cover crop treatment and the rate of fertilizer N applied to cover crops for both growing seasons (Tables 3-2, 3-3). When averaged across fertilizer N rates, corn TN accumulation in the 2014-2015 growing season followed a trend among cover crop treatments similar to that of corn biomass production. Corn TN uptake was greatest at 17 kg N ha^{-1} when planted into tillage radish residue and least at 1 kg N ha^{-1} when planted into cereal rye residue (Table 3-9). The almost 14-fold difference in mass of corn TN recovery between corn following tillage radish and corn following cereal rye could explain the large difference in aboveground growth measured in corn that followed the two cover crop monocultures. The large amount of TN recovered by corn planted after tillage radish can likely be attributed to the rapid decomposition and low C:N ratio (11:1 on average) of tillage radish residue, which supported favorable conditions for providing corn with plant-available N through mineralization. This is in contrast to Gieske et al. (2016), who observed that most of the tillage radish residue decomposed, but after being winterkilled, much of the NO_3-N recovered by tillage radish prematurely leached from the residue and was unavailable to the following corn crop at planting. Consequently, tillage radish did not significantly increase the N concentration in the subsequent corn biomass at the V8 growth stage compared to no cover crop.

Corn biomass production and TN recovery was lowest following cereal rye, which was more likely due to lack of decomposition from poor residue-to-soil contact than microbial immobilization of N. Most cereal rye residue did not break down by the time of corn biomass sampling. The large amount of biomass produced by cereal rye likely prevented residue from lying flat on the surface and limited direct contact with the soil for most of the residue. The average C:N ratio of cereal rye residue at the time of termination was 24:1, which would indicate that microbial immobilization of N from cereal rye would not necessarily be favored. Corn planted into tillage radish-cereal rye blend residue and corn planted into no cover crops contained similar amounts of TN and, on average, contained four times as much TN as corn planted into cereal rye residue (Table 3-9). The decrease in TN recovery by corn following cereal rye compared to corn following no cover crops illustrates that even though cereal rye captured at least 64 kg N ha^{-1}, most of the sequestered N was retained in the residue and unavailable to the following corn crop prior to the V6 growth stage. Although TN uptake and dry matter production differences were observed between corn planted into cereal rye and corn planted into tillage radish, the TN concentration of corn ranged from 1.5 to 2.6%, which is lower than the 3 to 4% TN concentration range deemed sufficient for early season corn (> 10 cm in height to tasseling) (Campbell and Plank, 2000). Therefore, N recycling from these cover crops alone likely cannot substitute fully for early N fertilization on corn, but rapid N recycling by tillage radish could supplement some of the needed pre- or at-planting N fertilization

Although the fertilizer N rate applied to the cover crops did not significantly influence the aboveground corn growth, corn tended to recover more TN, in general, as the amount of fertilizer N applied to the cover crops increased when averaged across cover crop treatments in the 2014-2015 growing season (Table 3-9). Similar results were obtained by McCracken et al. (1989), who observed that N fertilization increased the amount of TN uptake by corn following cereal rye and hairy vetch cover crops. Corn planted into cover crops that received the highest fertilizer N rate (101 kg N ha^{-1}) contained 9 kg N ha^{-1} of TN by the V6 stage, which was 20% greater, on average, than that of corn planted into cover crops that received 0 or 34 kg N ha^{-1} of fertilizer N (Table 3-9). The amount of fertilizer N applied to cover crops could have directly and/or indirectly influenced corn TN content through a few methods. Since the cover crops were not 100% efficient at recovering the applied fertilizer N, a small amount of labeled N remained in the soil to be utilized by the following corn crop (Table 3-8). As fertilizer N rate increased, the amount of TN stored in cover crop residue also increased, resulting in an increased organic N pool from which more N would be available upon mineralization.

In the 2015-2016 growing season, the mass of TN recovered by corn varied from 4 to 13 kg N ha^{-1} when averaged across fertilizer N rates (Table 3-9). Corn following tillage radish and the cover crop blend, which was dominated by tillage radish, contained at least three times more TN than corn planted into winter fallow (Table 3-9). The differences in corn TN uptake, as influenced by the cover crop, were likely attributed to the similar order of the magnitude of differences in corn dry matter production. The increased TN uptake by corn following managed cover crops compared to corn after a winter fallow illustrates that cover crops could improve the early-season N availability for the subsequent crop.

Total N uptake by corn in the 2015-2016 growing season also increased with the fertilizer N rate when averaged across cover crop treatments (Table 3-9). Corn TN uptake by V6 was maximized at 12 kg N ha^{-1} when at least 67 kg N ha^{-1} of fertilizer N was applied to the cover crops, and the mass of TN recovered by corn decreased by 23% when the cover crop did not receive fertilizer N (Table 3-9). Total N stored in cover crop residue also displayed a positive trend with fertilizer N rate, which could imply that some of the increase in corn TN content could be attributed to recycling of more N induced by the addition of fertilizer N to cover crops. Another potential source for the additional N recovered by corn at higher fertilizer N rates could be labeled fertilizer N in the soil that was not recovered by the cover crops. requirements.

Corn Fertilizer N Uptake and Recovery Efficiency

The mass of labeled fertilizer N recovered by corn ranged from 0 to 2 kg N ha^{-1} in the 2014-2015 growing season (Table 3-9). Corn following tillage radish in monoculture that received the greatest rate of fertilizer N recovered the greatest amount of labeled N (Table 3-9) despite the cover crop containing one of the least amounts of fertilizer N (4 kg N ha^{-1}) (Table 3-5). When compared to corn planted into soil after winter fallow, corn planted into tillage radish residue contained significantly greater amounts of fertilizer N on average (Table 3-9), but the amount of residual fertilizer N in the soil at the time of cover crop termination was not significantly different between soils containing tillage radish and fallow soils for each soil depth (Table 3-7). Therefore, the increase in fertilizer N uptake by corn after tillage radish can likely be attributed to the fast turnover of N by tillage radish instead of residual fertilizer N remaining in the soil after cover crop termination. Corn planted into cereal rye residue that stored the greatest amount of fertilizer N (32 kg N ha^{-1}) recovered significantly less labeled N (when 34 or 67 kg N ha^{-1} of fertilizer N was applied) than corn planted into tillage radish residue that contained only 4 kg N ha^{-1} (Table 3-9). Since the mass of fertilizer N recovered by corn planted into cereal rye and that of corn planted into fallow soil was similar (Table 3-9) and the amounts of fertilizer N remaining in the respective soils was not different between cereal rye and fallow treatments within the three upper 15-cm depth increments (Table 3-7), the decrease in fertilizer N recovery by corn following cereal rye compared to that of corn following tillage radish is likely a result of slower decomposition and release of captured fertilizer N by cereal rye residue.

Regardless of the cover crop species, corn following established cover crops recovered more labeled N as the rate of fertilizer N applied to the cover crops increased (Table 3-9). When preceded by tillage radish in monoculture and the cover crop blend, corn uptake of labeled N was proportional to the increase in the fertilizer N rate applied to cover crops (Table 3-9). Within each cover crop treatment, the mass of fertilizer N recovered by corn shoots was three times greater when tillage radish and cover crops in the blend received 101 kg N ha^{-1} of fertilizer N than when the respective cover crops received 34 kg N ha^{-1} of fertilizer N (Table 3-9). Similarly, a three-fold increase in the rate of fertilizer N applied to cereal rye contributed to a six-fold increase in fertilizer N uptake by the proceeding corn crop (Table 3-9). Within the upper four 15-cm incremental depths, significantly greater amounts of residual fertilizer N were found at the time of cover crop sampling in soils that received the maximum fertilizer N rate than soils to which only 34 kg N ha^{-1} of fertilizer N was applied (Table 3-8); therefore, more labeled N was available for corn uptake in soils that received 101 kg N ha^{-1}. Fertilizer N uptake by corn planted into fallow soil, however, was not significantly influenced by the rate of labeled N previously applied (Table 3-9). Although the top 45 cm of fallow soil contained similar amounts of residual fertilizer N as cover cropped soil, significantly greater amounts of labeled N were found in the 45- to 60-cm depth of fallow soils that received the maximum fertilizer N rate than any other soil (Table 3-8). The ten-fold increase in residual fertilizer N in the lower depth of fallow soils that received 101 kg N ha^{-1} could indicate that more leaching of labeled N below the effective rooting depth of the young corn plants (approximately 30 cm at V6 growth stage (Irmak and Rudnick, 2014)), which limited uptake of fertilizer N by corn.

The efficiency at which corn recovered fertilizer N in the 2014-2015 growing season was influenced by the cover crop treatment (Table 3-2). Corn FNRE ranged from 0 to 2% and followed trends similar to that of dry matter accumulation (Table 3-6). The FNRE of corn in this study is lower than the 2 to 11% range for FNRE of corn following crimson clover and cereal rye quantified in a study by Ranells and Wagger (1997). Although tillage radish in monoculture recovered the least mass of fertilizer N and had the lowest FNRE, the *Brassica* species contributed to the highest FNRE for the following corn (Table 3-6). Faster turnover of labeled N by tillage radish likely led to a greater percent of the fertilizer N applied to cover crops acquired by the following corn crop compared to corn planted into cereal rye or the cereal rye-dominated blend. Corn planted into the cover crop blend was less efficient than corn planted into tillage radish, but over five times more efficient than corn following cereal rye, and almost twice as efficient as corn planted into no cover crop (Table 3-6). The increase in FNRE of corn planted into the cereal rye-dominated blend compared to corn following cereal rye might indicate that faster decomposition and N recycling by tillage radishes in the blend partially compensated for the retention of fertilizer N by cereal rye. On average, corn following cereal rye was least efficient in recovering fertilizer N (Table 3-6), even though cereal rye sequestered the greatest amounts of labeled N. Since the FNRE of corn planted into cereal rye was three times lower than that of corn planted into soil without cover crops (Table 3-6), it can be concluded that a large portion of the fertilizer N acquired by cereal rye was retained in the residue and unavailable to the following corn crop through the early growth stages.

In the 2015-2016 growing season, corn fertilizer N uptake was not significantly influenced by the cover crop but varied from 1 to 2 kg N ha^{-1} with the rate of fertilizer N applied to cover crops (Table 3-9). Corn recovered approximately twice as much fertilizer N, on average, when cover crops received at least 67 kg N ha^{-1} than when the cover crops received 34 kg N ha^{-1} (Table 3-9). The increase in fertilizer N uptake by corn is similarly proportional to the increases in fertilizer N uptake by cover crops, which indicates that more labeled N was recovered and recycled by cover crops for the following corn crop to use as the fertilizer N rate increased. The cover crop significantly affected the efficiency at which corn recovered fertilizer N (Table 3-3). Corn following tillage radish and the cover crop blend recovered 3% of the applied fertilizer N, on average, which was almost four times more efficient than corn planted into no cover crop (Table 3-6). Soils with established cover crops contained approximately 19 times more residual labeled N than soil without cover crops in the 30- to 45- and 45- to 60-cm depths (Fig. 3-2), which indicates that fallow soils were more susceptible to leaching of fertilizer N than soils with cover crops despite the presence on native weeds in fallow soils. Therefore, much of the fertilizer N applied to fallow soils likely leached below the effective rooting depth of the young corn and contributed to a lower FNRE for corn in fallow soil.

Corn Soil N Uptake

The majority of TN recovered by corn in both growing seasons as unlabeled, residual soil N, and the mass of soil N contained in corn shoots was influenced by the cover crop in both growing seasons (Tables 3-2, 3-3). Since the mass of fertilizer N recovery by corn was often lower than the standard error for corn soil N uptake, the least square means for corn soil N uptake are identical to those of corn TN uptake for each cover crop treatment when averaged across fertilizer N rates (Table 3-9). Nevertheless, the differences in soil N uptake by corn induced by the cover crop provide insight into the native soil N recycling capabilities of these cover crop species. In the 2014-2015 growing season, corn following tillage radish recovered approximately 17 kg N ha^{-1} of soil N, which is nearly five times greater, on average, than that of corn following the blend and no cover crops and almost 14 times greater than that of corn planted into no cover crops (Table 3-9). The results indicate that tillage radish was the most effective at turning over available soil N early in the corn growing season, even though tillage radish was least effective at recovering soil N in the colder growing season. Corn planted into cereal rye residue only recovered 1 kg N ha^{-1} of soil N, which was nearly 25% of that recovered by corn planted into no cover crop (Table 3-9). The decrease in soil N acquisition by corn following cereal rye compared to corn following fallow signifies that most of the 64 kg N ha^{-1} of soil N recovered by cereal rye remained in the cover crop residue and was unavailable to the successive corn crop.

Similar results were obtained in the 2015-2016 growing season, in which corn following tillage radish in monoculture or the tillage radish-dominated blend contained the most soil N (12 kg N ha^{-1}) (Table 3-9). Tillage radish and cover crops in the blend recovered approximately 15 times more soil N (Table 3-5), on average, than native weeds in the fallow soils, but the following corn crop only contained three times more soil N (Table 3-9), on average, when planted into tillage radish and the blend than when planted into fallow. From the results, it appears that faster decomposition of tillage radish residue facilitated greater early-season growth and soil N recovery by the following corn crop than native weeds in fallow. The disproportionately lower increase in magnitude of soil N recovery by corn associated with tillage radish treatments compared to the increase in magnitude of soil N recovered tillage radish and cover crops in the blend can possibly be attributed to the earlier planting date of corn in the 2015-2016 growing season, which likely coincided with slower rates of organic N mineralization.

CONCLUSIONS

In the 2014-2015 growing season, tillage radish biomass accumulation was limited and prematurely terminated by cold minimum temperatures that frequently were below -4°C, while cereal rye thrived under the conditions by undergoing dormancy and resuming dry matter production in late winter. As a result, large differences in biomass production were observed between the two cover crop species, and cereal rye outgrew and outcompeted tillage radish in the blend during the 2014-2015 growing season. In the 2015-2016 growing season that was characterized by warmer fall and winter temperatures, differences in biomass accumulation between tillage radish and cereal rye were less evident. The dynamics of biomass accumulation in the monocultures and blend, as influenced by ambient temperature, highlight the complexities and risks associated with cover crop monocultures and blends. Growing cold-sensitive winter cover crops, like tillage radish, in monoculture creates the risks of limited biomass production and soil coverage, as well as premature termination and nutrient release, especially in colder climates. Dry matter produced by winter-hardy cover crops may compensate for limited biomass accumulation by cold-sensitive cover crops when grown together in a blend. Thus, cover crop blends with species of differing cold-tolerance thresholds could alleviate some risk associated with cold-sensitive cover crop monocultures, especially in transitional climate regions, like Arkansas, where the winter temperatures fluctuate frequently among years.

Dry matter production by cover crops largely dictated the capacity at which cover crops accumulated N. In the 2014-2015 growing season, cereal rye captured significantly greater masses of TN, fertilizer N, and soil N than tillage radish, on average, due to greater biomass accumulation. In the 2015-2016 growing season, however, TN and soil N uptake by cereal rye was significantly lower, on average, than that for tillage radish despite no significant difference in average biomass production between the species. The difference observed in TN uptake between cereal rye and tillage radish in the 2015-2016 growing season could be attributed to variations in the growth rate of above and below-ground plant tissue. Although, tillage radish and cereal rye accumulated similar amounts of dry matter that could serve as sinks for N, the warmer temperatures in the 2015-2016 growing season possibly accelerated the growth and nutrient acquisition for tillage radish faster than that of cereal rye. It is important to note that since root samples were not collected from cereal rye in this study, the actual amount of TN captured by cereal rye is possibly slightly greater than measured.

Biomass accumulation also governed the efficiency at which cover crops recovered fertilizer N. In the 2014-2015 growing season, 30% of the fertilizer N was recovered by cover crops, at most, and FNRE was maximized by the cover crop that produced the most dry matter, cereal rye. Results suggest that fall and winter growing conditions can alter the dynamics of FNRE by cover crops, especially for cold-sensitive species like tillage radish. Since cover crops were not completely efficient at recovering labeled N, much of the fertilizer N remained in the soil. Most of the residual fertilizer N remained in the top 15 cm of the soil, and some labeled N was found in the lowest sampled depth, which suggests that some leaching occurred. However, labeled N was much lower at the deeper layers under cover crops than fallow, which suggests that established cover crops decreased leaching of fertilizer N compared to that of fallow soil and highlights the utility of cover crops as catch crops. Furthermore, the application of fertilizer N to cover crops, especially when unnecessary to achieve adequate biomass, will add needless input costs for producers.

Early season dry matter production and N recovery by corn was largely influenced by cover crop species, which reflects differences in the N recycling efficiencies between tillage radish and cereal rye. In both growing seasons, tillage radish contributed to greater biomass accumulation, TN uptake, and soil N recovery by the following corn crop than cereal rye or no cover crop. Tillage radish released N rapidly into the soil, and as a result, provided available N for the subsequent corn to recover and utilize early in the growing season. Corn following cereal rye, however, produced less biomass and contained less TN and soil N at the V6 growth stage than corn following no cover crop, which indicates that most of the N captured by cereal rye was tied up in the cover crop residue and unavailable to the subsequent corn. Consequently, corn following cereal rye may need additional fertilizer N at planting to compensate for the lack of available N early in the growing season, especially when cover crop residue is surface applied into the soil, such as a no-till system.

Regardless of the intended goal for growing cover crops, the extent to which cover crops alter the early-season N flux for the subsequent cash crop and the compatibility of a cover crop in a production system should be considered when selecting a cover crop species. Based on the results from this study, a high N-demanding grass commodity crop like corn should be preceded by a cover crop, like tillage radish, that quickly decomposes and recycles N to encourage early season growth and N accumulation. If premature winterkill and nutrient turnover by tillage radish is a concern, tillage radish should be blended with cereal rye, especially before later-planted summer cash crops. Furthermore, application of N fertilizer to tillage radish is likely unnecessary and could exacerbate N leaching, particularly in soils with high amounts of residual N.

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TABLES AND FIGURES

Table 3-1. Temperature data for Kibler, AR in the 2014-2015 and 2015-2016 growing seasons.

Management Period	Number of Days	Mean Minimum Temperature†	Mean Maximum Temperature	Mean Average Temperature	Number of Days Below -4°C	Total Precipitation	Days With Precipitation Events
		°C				cm	
			2014-2015				
Cover Crop Planting to Cover Crop Sampling	189	3.4	15.1	8.9	26	70	51
Cover Crop Sampling to Corn Planting	30	11.7	23.3	17.5	0	11	12
Corn Planting to Corn Sampling	42	17.2	27.7	22.1	0	50	12
			2015-2016				
Cover Crop Planting to Cover Crop Sampling	157	5.1	18.0	11.2	8	61	33
Cover Crop Sampling to Corn Planting	32	6.2	20.3	13.4	0	12	11
Corn Planting to Corn Sampling	48	11.6	24.3	18.2	0	25	17

† Data were obtained from National Oceanic and Atmospheric Administration-National Center for Environmental Information (NOAA-NCEI) Climate Data Online (NOAA-NCEI, 2018). Daily weather readings were collected from the nearest available weather station, Fort Smith Regional Airport, AR (35°19'58.8"N, 94°21'45.0"W).

Table 3-2. Analysis of variance table for fixed effects in the 2014-2015 growing season at Kibler, AR.

Source	**Nparm†**	**DFNum**	**DFDen**	**F Ratio**	**Prob > F**
Cover Crop Biomass					
Cover Crop	2	2	29.2	49.1	<0.0001
Fertilizer N Rate	3	3	29.3	8.2	0.0004
Cover Crop by Fertilizer N Rate	6	6	29.3	7.4	<0.0001
Corn Biomass					
Cover Crop	3	3	40.9	63.7	<0.0001
Fertilizer N Rate	3	3	41.1	2.6	0.0667
Cover Crop by Fertilizer N Rate	9	9	41.1	0.4	0.9438
Cover Crop TN Uptake					
Cover Crop	2	2	29.4	14.9	<0.0001
Fertilizer N Rate	3	3	29.7	6.9	0.0012
Cover Crop by Fertilizer N Rate	6	6	29.7	6.1	0.0003
Corn TN Uptake					
Cover Crop	3	3	40.8	81.3	<0.0001
Fertilizer N Rate	3	3	41.0	4.1	0.0123
Cover Crop by Fertilizer N Rate	9	9	41.1	0.7	0.7417
Cover Crop Fertilizer N Uptake					
Cover Crop	2	2	18.1	3.3	0.0619
Fertilizer N Rate	2	2	19.0	29.2	<0.0001
Cover Crop by Fertilizer N Rate	4	4	18.8	7.5	0.0009
Corn Fertilizer N Uptake					
Cover Crop	3	3	29.0	7.8	0.0006
Fertilizer N Rate	2	2	29.0	54.6	<0.0001
Cover Crop by Fertilizer N Rate	6	6	29.0	6.9	0.0001
Cover Crop Soil N Uptake					
Cover Crop	2	2	29.4	15.8	<0.0001
Fertilizer N Rate	3	3	29.6	0.1	0.9707
Cover Crop by Fertilizer N Rate	6	6	29.7	2.3	0.0573
Corn Soil N Uptake					
Cover Crop	3	3	40.8	94.6	<0.0001
Fertilizer N Rate	3	3	41.1	1.3	0.2977
Cover Crop by Fertilizer N Rate	9	9	41.1	0.9	0.5245
Cover Crop FNRE					
Cover Crop	2	2	19.5	12.4	0.0003
Fertilizer N Rate	2	2	19.8	0.4	0.6797
Cover Crop by Fertilizer N Rate	4	4	19.9	1.2	0.3447
Corn FNRE					
Cover Crop	3	3	28.8	29.8	<0.0001
Fertilizer N Rate	2	2	28.9	0.4	0.7060
Cover Crop by Fertilizer N Rate	6	6	28.9	2.1	0.0820

† Nparm, number or parameters; DFNum, degrees of freedom for numerator; DFDen, degrees of freedom for denominator

Table 3-3. Analysis of variance table for fixed effects in the 2015-2016 growing season at Kibler, AR.

Source	Nparm	DFNum	DFDen	F Ratio	Prob > F
Cover Crop Biomass					
Cover Crop	3	3	43.0	42.4	<0.0001
Fertilizer N Rate	3	3	43.1	0.3	0.8602
Cover Crop by Fertilizer N Rate	9	9	43.2	2.4	0.0258
Corn Biomass					
Cover Crop	2	2	31.5	18.2	<0.0001
Fertilizer N Rate	3	3	31.9	2.1	0.1179
Cover Crop by Fertilizer N Rate	6	6	32.0	1.4	0.2465
Cover Crop TN Uptake					
Cover Crop	3	3	42.9	48.2	<0.0001
Fertilizer N Rate	3	3	43.2	3.7	0.0178
Cover Crop by Fertilizer N Rate	9	9	43.3	1.6	0.1528
Corn TN Uptake					
Cover Crop	2	2	30.7	20.2	<0.0001
Fertilizer N Rate	3	3	30.8	4.5	0.0103
Cover Crop by Fertilizer N Rate	6	6	31.0	1.5	0.1976
Cover Crop Fertilizer N Uptake					
Cover Crop	3	3	31.0	3.0	0.0465
Fertilizer N Rate	2	2	31.6	23.4	<0.0001
Cover Crop by Fertilizer N Rate	6	6	31.7	1.4	0.2367
Corn Fertilizer N Uptake					
Cover Crop	2	2	22.1	2.6	0.0950
Fertilizer N Rate	2	2	22.2	8.9	0.0014
Cover Crop by Fertilizer N Rate	4	4	22.2	0.8	0.5089
Cover Crop Soil N Uptake					
Cover Crop	3	3	42.9	67.6	<0.0001
Fertilizer N Rate	3	3	43.0	8.8	0.0001
Cover Crop by Fertilizer N Rate	9	9	43.1	1.9	0.0766
Corn Soil N Uptake					
Cover Crop	2	2	30.7	22.9	<0.0001
Fertilizer N Rate	3	3	30.9	0.7	0.5675
Cover Crop by Fertilizer N Rate	6	6	31.0	0.9	0.4872
Cover Crop FNRE					
Cover Crop	3	3	31.0	14.0	<0.0001
Fertilizer N Rate	2	2	31.1	1.9	0.1666
Cover Crop by Fertilizer N Rate	6	6	31.2	1.1	0.3803
Corn FNRE					
Cover Crop	2	2	22.1	9.0	0.0014
Fertilizer N Rate	2	2	22.2	1.0	0.3935
Cover Crop by Fertilizer N Rate	4	4	22.2	0.4	0.8274

† Nparm, number or parameters; DFNum, degrees of freedom for numerator; DFDen, degrees of freedom for denominator

Table 3-4. Biomass accumulation by cover crops at termination and corn at the V6 growth stage in the 2014-2015 and 2015-2016 years at Kibler, AR.

Cover Crop	Fertilizer N Rate	Cover Crop Biomass†	Corn Biomass
	kg N ha^{-1}	kg ha^{-1}	
2014-2015			
Tillage Radish	0	1176 f	1090 a
	34	1429 f	
	67	1045 f	
	101	772 f	
Tillage Radish/Cereal Rye	0	3996 e	276 b
	34	3913 e	
	67	4305 de	
	101	4750 cd	
Cereal Rye	0	3842 e	53 c
	34	5029 bc	
	67	5602 b	
	101	6350 a	
Fallow	0	-	302 b
	34		
	67		
	101		
2015-2016			
Tillage Radish	0	6263 abc	584 a
	34	5890 abcd	
	67	5748 abcd	
	101	5978 abcd	
Tillage Radish/Cereal Rye	0	6100 abcd	401 b
	34	6746 a	
	67	6650 ab	
	101	5033 d	
Cereal Rye	0	5646 bcd	-
	34	5543 cd	
	67	5789 abcd	
	101	5901 abcd	
Fallow	0	1414 f	179 c
	34	1750 f	
	67	2101 ef	
	101	2968 e	

† Means followed by the same lowercase letter are not significantly different at $P < 0.05$ within a year for a given response variable.

Table 3-5. Mass of total N (TN), fertilizer N, and soil N recovered by cover crops at termination at Kibler, AR in the 2014-2015 and 2015-2016 growing seasons.

Cover Crop	**Fertilizer N Rate**	**Cover Crop TN Uptake†**	**Cover Crop Fertilizer N Uptake**	**Cover Crop Soil N Uptake‡**
	kg N ha^{-1}			
		2014-2015		
Tillage Radish	0	34 f	-	34 b
	34	42 f	3 e	
	67	32 f	4 e	
	101	25 f	4 de	
Tillage Radish/ Cereal Rye Blend	0	76 cde	-	76 a
	34	73 de	5 de	
	67	88 bcd	13 c	
	101	93 bc	23 b	
Cereal Rye	0	64 e	-	64 a
	34	82 cd	10 cd	
	67	102 ab	24 b	
	101	117 a	32 a	
		2015-2016		
Tillage Radish	-	135 a	17 ab	135 a
Tillage Radish/ Cereal Rye Blend		123 a	23 a	123 a
Cereal Rye		98 b	17 ab	98 b
Fallow		9 c	5 b	9 c
-	0	91 b	-	91 a
	34	102 ab	16 c	86 a
	67	111 a	28 b	83 a
	101	103 ab	37 a	66 b

† Means followed by the same lowercase letter are not significantly different at $P < 0.05$ within a year for a given fixed effect.

‡ Cover crop soil N was averaged across fertilizer N rates for each cover crop treatment in the 2014-2015 growing season due to lack of significant interaction.

Table 3-6. Fertilizer N Recovery Efficiency (FNRE) of cover crops and corn at Kibler, Arkansas in the 2014-2015 and 2015-2016 growing seasons.

Cover Crop	**Cover Crop FNRE†**	**Corn FNRE**
	—————%—————	
	2014-2015	
Tillage Radish	10 b	2 a
Tillage Radish/ Cereal Rye Blend	18 b	1 b
Cereal Rye	30 a	0 d
Fallow	-	1 c
	2015-2016	
Tillage Radish	50 b	3 a
Tillage Radish/ Cereal Rye Blend	68 a	3 a
Cereal Rye	48 b	-
Fallow	15 c	1 b

† Means followed by the same lowercase letter are not significantly different within a year at $P < 0.05$.

Table 3-7. Analysis of variance table for the mass of fertilizer N remaining in the soil at the time of cover crop termination in the 2014-2015 and 2015-2016 growing seasons at Kibler, AR.

Depth Interval	Source	Nparm	DFNum	DFDen	F Ratio	Prob > F
—cm—						
			2014-2015			
0-15	Cover Crop	3	3	29.6	1.5	0.2353
	Fertilizer N Rate	2	2	29.6	7.6	0.0021
	Cover Crop by Fertilizer N Rate	6	6	29.7	2.1	0.0900
15-30	Cover Crop	3	3	29.3	0.3	0.8182
	Fertilizer N Rate	2	2	29.4	5.1	0.0123
	Cover Crop by Fertilizer N Rate	6	6	29.5	1.0	0.4559
30-45	Cover Crop	3	3	28.2	0.1	0.9407
	Fertilizer N Rate	2	2	28.0	6.2	0.0060
	Cover Crop by Fertilizer N Rate	6	6	28.2	0.9	0.5417
45-60	Cover Crop	3	3	27.9	0.1	0.9425
	Fertilizer N Rate	2	2	27.8	5.1	0.0128
	Cover Crop by Fertilizer N Rate	6	6	27.9	3.1	0.0192
			2015-2016			
0-15	Cover Crop	3	3	7.1	0.5	0.7031
15-30	Cover Crop	3	3	7.9	0.5	0.7187
30-45	Cover Crop	3	3	7.5	33.4	0.0001
45-60	Cover Crop	3	3	7.2	8.0	0.0109

Table 3-8. Mass of fertilizer N remaining in the 0- to 15-, 15- to 30-, 30- to 45-, and 45- to 60-cm soil depth intervals at the time of cover crop sampling in the 2014-2015 growing season at Kibler, AR.

Soil Depth Interval	**Cover Crop†**	**Fertilizer N Rate**	**Fertilizer N Remaining in Soil‡**
cm		kg N ha^{-1}	
0-15	-	34	8 b
		67	13 a
		101	17 a
15-30	-	34	1 b
		67	2 ab
		101	4 a
30-45	-	34	0 b
		67	1 b
		101	2 a
45-60	Tillage Radish	34	1 b
		67	1 b
		101	1 b
	Tillage Radish/ Cereal Rye Blend	34	0 b
		67	1 b
		101	1 b
	Cereal Rye	34	1 b
		67	1 b
		101	1 b
	Fallow	34	1 b
		67	0 b
		101	6 a

† Values were average across cover crop treatments for each fertilizer N treatment for the 0- to 15-, 15- to 30-, and 30- to 45-cm soil depth intervals.

‡ Means followed by the same lowercase letter are not significantly different within a soil depth at $P < 0.05$.

Table 3-9. Mass of total N (TN), fertilizer N, and soil N recovered by corn at the V6 growth stage at Kibler, AR in the 2014-2015 and 2015-2016 growing seasons.

Cover Crop	**Fertilizer N Rate**	**Corn TN Uptake†**	**Corn Fertilizer N Uptake**	**Corn Soil N Uptake**
	kg N ha^{-1}			
	2014-2015			
Tillage Radish	0	17 a	-	17 a
	34		0 c	
	67		1 b	
	101		2 a	
Tillage Radish/Cereal Rye	0	6 b	-	6 b
	34		0 cd	
	67		1 c	
	101		1 b	
Cereal Rye	0	1 c	-	1 c
	34		0 e	
	67		0 de	
	101		1 c	
Fallow	0	4 b	-	4 b
	34		0 de	
	67		0 de	
	101		0 cd	
-	0	7 b	-	-
	34	8 b		
	67	8 ab		
	101	9 a		
	2015-2016			
Tillage Radish	-	13 a	-	13 a
Tillage Radish/Cereal Rye		11 a		11 a
Cereal Rye		-		-
Fallow		4 b		4 b
-	0	9 b	-	-
	34	11 ab	1 b	
	67	12 a	2 a	
	101	12 a	2 a	

† Means followed by the same lowercase letter are not significantly different at $P < 0.05$ within a year and fixed effect for a given response variable.

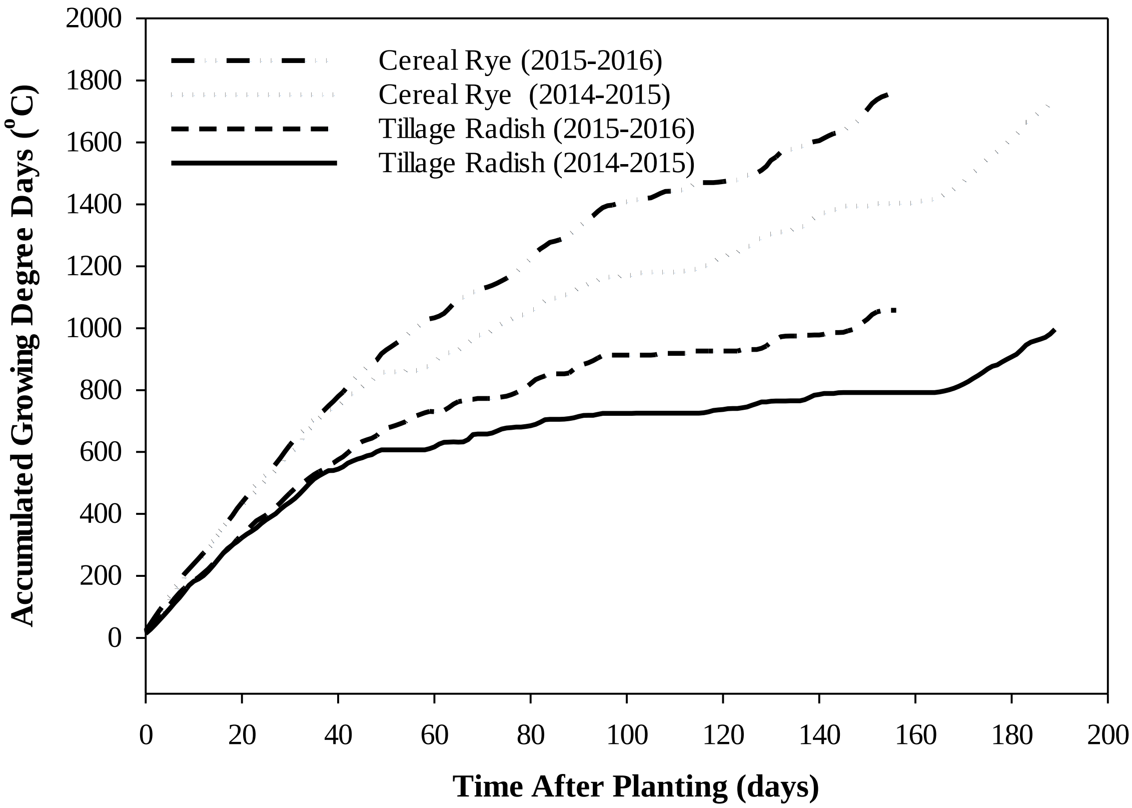

Figure 3-1. Growing degree days accumulated by cover crops from planting to termination in years 2014-2015 and 2015-2016 at Kibler, Arkansas. Growing degree days were calculated using base temperatures of 0°C for cereal rye and 5°C for tillage radish. Data were obtained from National Oceanic and Atmospheric Administration-National Center for Environmental Information (NOAA-NCEI) Climate Data Online (NOAA-NCEI, 2018).

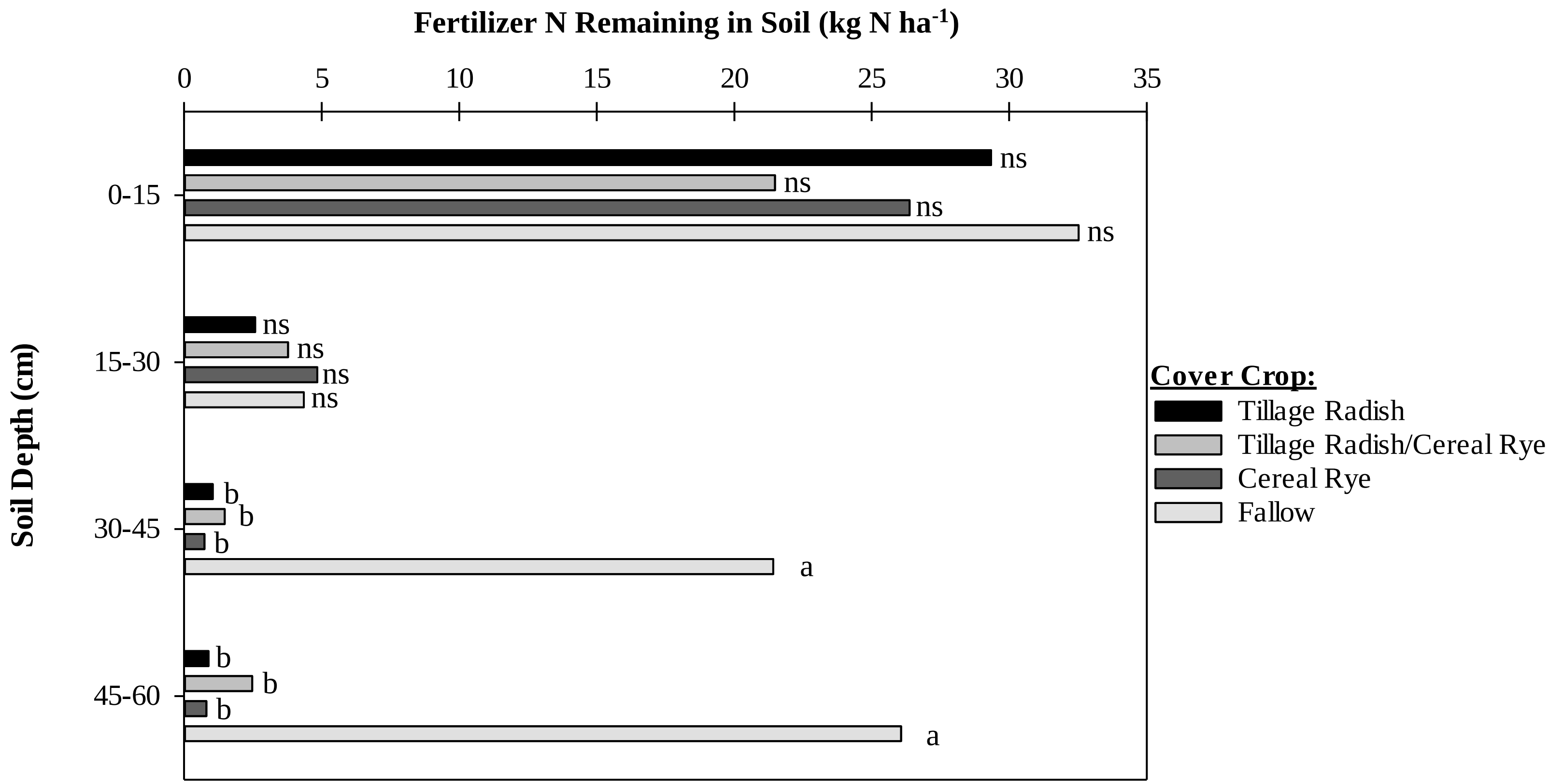

Figure 3-2. Mass of fertilizer N remaining in the soil within four soil depth increments at the time of cover crop sampling after 101 kg N ha^{-1} of fertilizer was applied to cover crops in the 2015-2016 growing season at Kibler, AR. Fertilizer N values were compared among cover crop treatments within each soil depth increment. Bars with 'ns' or the same lowercase are not significantly different within a given soil depth increment ($P < 0.05$).

CHAPTER 4

Cover Crop Contributions to Early Season Nutrient Recycling in a No-Till Corn System II: Phosphorus, Potassium, And Zinc

ABSTRACT

Cover crops can conserve nutrients in a cash crop system by scavenging and releasing residual soil nutrients for the following commodity crop to utilize. The extent to which cover crops recycle N has been widely studied, but the capacity of cover crops to accumulate and provide other essential macro- and micronutrients has not been extensively reported; therefore, this experiment was established to investigate the recovery of phosphorus (P), potassium (K), and zinc (Zn) by cover crops and subsequent early-season uptake by the following corn (*Zea mays*) in a no-till system. Four cover crop treatments were included: tillage radish (*Raphanus sativus*), cereal rye (*Secale cereale*), a blend of tillage radish and cereal rye, and no cover crop. Soon after planting, cover crops received four fertilizer N rate treatments (0, 34, 67, or 101 kg N ha^{-1}) to assess the effect of N availability on the acquisition of P, K, and Zn. Corn was planted directly into cover crop residue using a no-till drill 4 wk after cover crop termination in the spring, and the uptake of P, K, and Zn by corn was determined at the V6 growth stage. Cover crops accumulated at most 35 kg P ha^{-1}, 62 kg K ha^{-1}, and 0.153 kg Zn ha^{-1}. Cereal rye captured more P, K, and Zn than tillage radish in the 2014-2015 growing season since tillage radish growth was limited by winterkill. Tillage radish accumulation of P, K, and Zn exceeded that of cereal rye in the 2015-2016 growing season when fall and winter temperatures were warmer and extensive winterkill did not occur. Application of fertilizer N to cover crops increased uptake of Zn by all cover crops in the 2015-2016 growing season; however, the amount of fertilizer N applied to cover crops did not influence P, K, and Zn uptake by the following corn, which indicates that fertilizer N was an unnecessary input for cover crops in this system as it relates to corn acquisition of other plant essential nutrients. Tillage radish significantly increased corn uptake of P, K, and Zn in both growing seasons by at most 300%, 489%, and 50%, respectively,

while cereal rye decreased subsequent corn nutrient uptake when compared to no cover crop. Results from this study imply that tillage radish is more effective than cereal rye at recycling P, K, and Zn early in the growing season to corn managed under no-till production.

INTRODUCTION

Cover crops are being utilized as multi-purpose tools that promote long-term sustainability in cropping systems. A major role that cover crops serve in row crop systems is as catch crops that preserve soil fertility and mitigate environmental consequences by capturing residual nutrients that could otherwise be lost from bare soil when cash crops are not grown (Dabney et al., 2001; Dean and Weil, 2009; Dabney et al., 2010). The captured nutrients are eventually recycled for use by following commodity crops after cover crop residue decomposes. Asynchrony between the release of available nutrients from cover crop residue and the following cash crop's nutrient demand could exacerbate nutrient loss from the soil system (Miller et al., 1994) and result in reduced growth and productivity of the following commodity crop (Dapaah and Vyn, 1998; Vyn et al., 1999; Kuo and Jellum, 2002). Understanding the role that cover crops play in changing the dynamics of nutrients in a cash crop system is important in making adjustments to fertilizer programs and avoiding reduced productivity and unintended nutrient losses.

High cash crop demand of P and K by corn and low soil availability of P and Zn often makes supplemental fertilization of these nutrients vital to maximize corn production in the Mid-South. Recommended rates of P, K, and Zn fertilizer for corn in Arkansas are typically 25 to 50 kg P ha^{-1}, 47 to 188 kg K ha^{-1}, and 11 kg Zn ha^{-1} (Espinoza and Ross, 2008). The extent to which cover crops recycle P, K, and Zn and the influence of cover crops on the following crop's P, K, and Zn fertilizer requirements have been relatively unexplored; however, some literature has investigated the means with which cover crops can affect the availability of P (Grinsted et al., 1982; Hedley et al., 1982; White and Weil, 2010; White and Weil, 2011), which could provide insight into the potential for increasing the availability of other nutrients using cover crops. Previous research has concluded that root exudates from *Brassica* species can induce changes in the rhizosphere that increase P availability (Grinsted et al., 1982; Hedley et al., 1982; White and Weil, 2011). Grinsted et al. (1982) and Hedley et al. (1982) showed that rape (*Brassica napus*, var. Emerald) seedlings increased the concentration of labile P in the rhizosphere at least ten times more than the control by decreasing the rhizosphere pH by as much as 2.4 units. White and Weil (2011) confirmed that another *Brassica* species, forage radish (also known as tillage radish), increased the available P in the soil immediately surrounding the channels left by taproots (within 3 cm) after decomposition when compared to no cover crop and bulk soil between forage radish rows; the authors concluded that living and decaying taproots released organic acids that solubilized P, which increased the concentration of available P around the taproots. The localized acidifying effect of *Brassica* root exudates could also potentially increase the availability of micronutrients like Zn, since Zn solubility is limited in neutral to high pH soils; however, research is still needed to assess the efficacy of cover crop root exudates on micronutrient availability.

Cover crops can also alter nutrient availability by facilitating improved access to nutrients for the following commodity crop, particularly when tillage is minimized. Some cover crop species provide a favorable soil environment for the growth and development of mycorrhizal fungi, which can subsequently colonize the roots of the following cash crop (Kabir and Koide, 2002; White and Weil, 2010). Mycorrhizae have been shown to increase the nutrient acquisition for the crop by supplying nutrients that might otherwise be outside the reach of the crop roots through extended growth and nutrient uptake by the fungal hyphae (Kabir and Koide, 2002; White and Weil, 2010). White and Weil (2010) found that corn following cereal rye cover crops in a no-till system had greater colonization of arbuscular mycorrhizal fungi at the V4 growth stage than corn following no cover crop in at least half of the site years. As a result, P concentration in corn shoots at the V4 and V8 growth stages was positively related to arbuscular mycorrhizal fungi colonization of corn roots. In other ways, cover crops help the following crop roots access nutrients by remobilizing and recycling nutrients. Actively growing cover crops may mine residual nutrients from the soil profile and store most of the recovered nutrients in aboveground biomass (White and Weil, 2011; Sievers and Cook, 2018). As a result, a majority of the nutrients from decaying cover crops in no-till systems are released on the soil surface or in the upper soil layers where the nutrients are easily accessible to the roots of the following cash crops early in the growing season (White and Weil, 2011). In a study by White and Weil (2011), P uptake in forage radish shoots accounted for at least 76% of the total P uptake in three of the four site years in which root samples were collected. Consequently, P concentration within the top 2.5 cm of bulk soil increased significantly after three years of forage radish cover crops in a no-till system.

Regardless of the method by which cover crops influence the availability of nutrients, knowing how individual cover crop species and cover crop blends affect the nutrient uptake and growth of the following cash crop is vital to make sound management decisions. For corn produced in the Mid-South, P, K, and Zn are essential nutrients that are often supplemented using fertilizer to avoid deficiencies and maximize productivity. Investigating the role of cover crops in recycling these nutrients in a cropping system can provide insight into how cover crops alter the nutrient dynamics and possible supplemental fertilizer needs of corn. Research that investigates the P, K, and Zn recycling by cover crops in a no-till corn system is lacking in the Mid-South; therefore, this study was established to assess the early-season contributions of cereal rye and tillage radish cover crops to P, K, and Zn recovery by no-till corn.

MATERIALS AND METHODS

Experimental Design

The field experiment was established at the Vegetable Research Station in Kibler, Arkansas (35°22'44.7"N, 94°13'56.9"W) on a soil classified as a Roxana silt loam (*Coarse-silty, mixed, superactive, nonacid, thermic Typic Udifluvents*) (Soil Survey Staff, 2015). Initial chemical analyses of the top 15 cm of the soil in the 2014-2015 and 2015-2016 growing seasons indicate that the soil on this site had pH values of 7.4 and 7.2 and contained 72 and 67 mg P kg^{-1}, 130 and 114 mg K kg^{-1}, and 4.0 and 2.3 mg Zn kg^{-1}, respectively (Mehlich-3 extractable nutrients (Zhang et al., 2014)). The study was arranged in a randomized complete block design with treatments in a four by four factorial structure. Treatment combinations were replicated four times and included four cover crop treatments (tillage radish, cereal rye, tillage radish/cereal rye blend, and fallow) and four fertilizer N rates (0, 34, 67, and 101 kg N ha^{-1}) in plots measuring 1.5 m by 3 m. The field in which the plots were established had previously been fallow for approximately one year.

Field Methods

A no-till drill (Hege 1000 series, Wintersteiger Seedmech, Ried im Innkreis, Austria) was used to establish cover crops on 24 Sept. 2014 and 23 Sept. 2015 in 23 cm-wide rows. Tillage radish in monoculture was seeded at the rate of 10 kg ha^{-1}, while cereal rye in monoculture was seeded at a rate of 103 kg ha^{-1}. When planted in the blend, cover crops were seeded at half of the rate of the respective monocultures. One week after cover crop establishment, urea treated with a urease inhibitor at a rate of 0.89 g N-(n-butyl) thiophosphoric triamide (NBPT) kg^{-1} urea [Agrotain Ultra (285 g NBPT L^{-1}), Koch Fertilizer LLC., Wichita, KS] was applied at the aforementioned N rates.

Biomass samples of cover crops were collected on 31 March 2015 and 26 Feb. 2016 from 91-cm sections of the middle four rows (0.84 m^2 area) in one half of each microplot. Whole tillage radish plants were harvested and separated into shoots and roots, while only the aboveground biomass of the cereal rye was collected. In 2016, a sufficient stand of weeds (henbit (*Lamium amplexicaule*) and annual bluegrass (*Poa annua*)) was present in fallow plots so aboveground biomass samples of the weeds were also collected by cutting weed shoots at the soil surface in a 0.84 m^2 section from one half of each fallow plot. On the day after cover crop biomass sampling, the remaining cover crops were terminated using glyphosate (N-(phosphonomethyl) glycine, 0.8 kg a.e. ha^{-1}) in 2015. In the 2015-2016 growing season, cover crops were killed using an application of glyphosate the day after sampling and a following application of paraquat (1,1´-dimethyl-4,4´-bipyridinium ion, 0.5 kg a.i. ha^{-1}) approximately 1 wk after sampling. Cover crop residue was also rolled to press cover crop residue to the soil surface and break off tillage radish taproots that were exposed above the surface. Approximately four weeks after cover crop termination, corn (var. Pioneer 1319HR (Pioneer Hi-Bred International, Johnston, IA)) was seeded directly into the cover crop residue with a no-till drill (Hege 1000 series, Wintersteiger Seedmech, Ried im Innkreis, Austria) at 87,000 seeds ha^{-1} in 91 cm-wide rows, which resulted in two rows per plot. Corn was planted ≥ 5 cm to prevent lodging and was irrigated as needed by a linear overhead sprinkler. Aboveground biomass corn samples were collected at V6 maturity stage in 91-cm sections of both rows (1.65 m^2 area) from the half of each plot in which cover crop samples were not collected.

Sample Analysis

Cover crop and corn samples were dried to a constant weight (for approximately 10 d) at 60°C and weighed. The dry weight was divided by the sampling area and extrapolated to kg ha^{-1} in order to determine the amount of dry matter produced. Plant samples were then ground and passed through a 2-mm sieve. Prepared plant and soil samples obtained from the field experiment were analyzed for P, K, and Zn using HNO_3 digestion (Jones, 1991) and a Spectro Arcos ICP (SPECTRO Analytical Instruments GmbH, Germany). The nutrient (P, K, and Zn) uptake (kg ha^{-1}) by cover crops and corn was calculated by multiplying the biomass by the respective nutrient concentration determined by the total plant digestion and ICP analysis. Since fertilizers containing P, K, and Zn were not applied to the cover crops, it can be assumed that nutrients recovered by cover crops originated in the soil.

Data Analysis

Cover crop data from the field experiment were analyzed using JMP Pro 13 using mixed models with replication as a random effect and cover crop, fertilizer N rate, and cover crop by fertilizer N rate as the fixed effects. The influence of cover crop, fertilizer N rate, and cover crop by fertilizer N rate on the uptake of P, K, and Zn by cover crops and corn were assessed. Data were analyzed separately for each growing season due to dissimilarities in degrees of freedom caused by differences in the number of cover crop and corn samples collected. Significant differences among means were separated using Student’s T pairwise comparison and a significance level of 0.05.

RESULTS AND DISCUSSION

Phosphorus Uptake by Cover Crops

The mass of P recovered by cover crops was significantly influenced by the cover crop by fertilizer N rate interaction (Table 4-1) and ranged from 5 to 23 kg P ha^{-1} (Table 4-2) in the 2014-2015 growing season. Phosphorus uptake by tillage radish, cover crops in the blend, and cereal rye were at least 5, 18, and 13 kg P ha^{-1}, respectively (Table 4-2). On average, P uptake was significantly greater for cereal rye in monoculture and cover crops in the blend than for tillage radish in monoculture. The trends observed in the first year of this study contrast that of White and Weil (2011) who found that total tillage radish P uptake (shoots plus roots) was nearly twice that of cereal rye shoots, on average, even though total tillage radish dry matter was only 13% greater than aboveground cereal rye dry matter, on average. Cover crops, except tillage radish in monoculture, showed a positive response in P uptake to increasing rates of fertilizer N. The highest amounts of P (20 kg P ha^{-1}, on average) were recovered by cereal rye in monoculture and cover crops in the blend that received at least 67 kg N ha^{-1} of fertilizer N, whereas tillage radish in monoculture to which at least 67 kg N ha^{-1} was applied recovered the least amounts of P (7 kg P ha^{-1}, on average) (Table 4-2). The differences in P uptake among cover crops reflect variations in growth and biomass accumulation, and the response of cover crop growth to the addition of fertilizer N in the 2014-2015 growing season. The lesser P uptake by tillage radish compared to the other cover crop treatments can be explained by the limited growth and biomass accumulation that resulted from colder winter temperatures and winterkill of many tillage radishes prior to biomass sampling and nutrient analysis in the spring. Cereal rye, on the other hand, was more tolerant of the lower winter temperatures in the 2014-2015 growing season, which allowed for greater biomass accumulation than tillage radish. As a result, cereal rye dominated the blend and acquired more P in aboveground tissue than tillage radish.

Dry matter production of cereal rye and cover crops in the cereal rye-dominated blend responded positively to addition of fertilizer N (Table 3-4), which can explain similar positive responses of P uptake by cereal rye and cover crops in the blend to fertilizer N rates. Tillage radish growth and biomass production did not respond to increasing fertilizer N rates, and a significant decrease in the mass of P recovered by tillage radish was observed with the addition of the highest fertilizer N rate (Table 4-2). The decline in P stored in tillage radish at greater fertilizer N rates could likely be attributed to increased winterkill of tillage radish at the higher fertilizer N rates and premature leaching of P from the residue prior to biomass sampling and nutrient analysis. Similar observations were observed by Miller et al. (1994), in which 30% of the captured P leached from oilseed radish (*Raphanus sativus* L. var. oleifera DC Metzg) residue following freezing.

Recovery of P by cover crops in the 2015-2016 growing season was significantly influenced by cover crop species (Table 4-3) and ranged from 2 to 35 kg P ha^{-1} (Table 4-2). Although established cover crops accumulated similar amounts of dry matter, significant differences in P recovery between cover crop species were observed in the 2015-2016 growing season. Total tillage radish P uptake averaged 35 kg P ha^{-1}, which was significantly greater than that of cereal rye shoots (18 kg P ha^{-1}) (Table 4-2). Results in the 2015-2016 growing season of this study are greater than that of White and Weil (2011), in which average total tillage radish and aboveground cereal rye P uptake was approximately 21 and 12 kg P ha^{-1}, respectively. Cover crops in the tillage radish-dominated blend recovered a similar amount of P as tillage radish but 60% more P than cereal rye (Table 4-2). Managed cover crops recovered approximately 10 to 20 times more P than native weeds, which highlights the role of established cover crops in conserving residual soil P between summer cash crops.

Potassium Uptake by Cover Crops

Potassium recovery by cover crops in the 2014-2015 growing season varied considerably with cover crop by fertilizer N rate (Table 4-1) from 9 to 152 kg K ha^{-1} (Table 4-2). Cover crops in the cereal rye-dominated blend and cereal rye in monoculture acquired significantly greater masses of K than tillage radish in monoculture, on average. Cereal rye and tillage radish K uptake ranged from 85 to 152 kg K ha^{-1} and from 9 to 40 kg K ha^{-1}, respectively, while K uptake in the blend averaged 116 kg K ha^{-1} (Table 4-2). The distinct and large differences in K uptake among cover crop species can likely be attributed to dry matter accumulation and cold tolerance. The colder winter temperatures in the 2014-2015 growing season provided favorable conditions for cereal rye growth and K acquisition; however, biomass and K accumulation and retention for tillage radish was limited by colder temperatures. Since K exists as an ion and is not associated with structural or organic compounds in the plant, K can readily leach from plant residue (Marschner, 1995). Winterkill and decay of tillage radishes prior to sample collection could have facilitated leaching of assimilated K from tillage radish residue before biomass sampling, which likely resulted in an underestimation of the K sequestered by tillage radish in the 2014-2015 growing season. The mass of K stored in cereal rye residue at the time of termination responded positively to the application of fertilizer N. Cereal rye that received the highest fertilizer N rate accumulated the greatest mass of K, which is likely the result of maximum dry matter production (Table 4-2). However, the uptake of K by cover crops in the blend was not significantly affected by fertilizer N rate. The mass of K contained in tillage radish decreased by approximately 75%

when the highest fertilizer N rate was applied (Table 4-2), which is likely a result of greater winterkill of tillage radishes that received the higher fertilizer N rates.

Cover crop uptake of K in the 2015-2016 was also influenced by the interaction of cover crop species and fertilizer N rate (Table 4-3). The mass of K content in established cover crops ranged from 102 to 162 kg K ha^{-1}, while the amount of K recovered by native weeds in fallow plots averaged 18 kg K ha^{-1} (Table 4-2). Planting cover crops resulted in six times more K captured than that accumulated by native weeds, which highlights the mining and storage ability of established cover crops. Maximum accumulation of K occurred when cover crops in the tillage radish-dominated blend received no more than 67 kg N ha^{-1} of fertilizer N (Table 4-2). On average, K sequestration by tillage radish in monoculture and cover crops in the blend was at most 147 and 162 kg K ha^{-1}, respectively. Cover crop K recovery in treatments containing tillage radish did not positively respond to fertilizer N application, and K uptake decreased significantly for the blend when the highest fertilizer N rate was applied (Table 4-2) which mirrors the trend observed for dry matter production. Cereal rye recovery of K averaged 109 kg K ha^{-1} and was not significantly influenced by fertilizer N rate. Although aboveground biomass accumulation was similar among the cover crop species, K recovery by tillage radish and cover crops in the blend was significantly greater than that by cereal rye, on average.

Zinc Uptake by Cover Crops

Zinc recovery by cover crops in the 2014-2015 growing season followed trends similar to that of P uptake and dry matter production. Cover crop Zn uptake ranged from 46 to 101 g Zn ha^{-1} (Table 4-2), and significant cover crop by fertilizer N interaction effects were observed (Table 4-1). Tillage radish in monoculture accumulated 51 g Zn ha^{-1}, on average, which was the lowest mean mass of Zn recovered by the cover crop treatments. Similar to all other nutrients measured, Zn uptake by tillage radish was limited by low dry matter production due to persistently low temperatures and winterkill that occurred at least 2 mo prior to chemical termination. Cover crops in the cereal-rye dominated blend captured 81 g Zn ha^{-1} on average, and the addition of fertilizer N did not significantly increase the mass of Zn acquired by cover crops in the blend (Table 4-2). When cereal rye in monoculture received at least 34 kg N ha^{-1}, Zn uptake by cereal rye was similar to that of cover crops in the blend, but greater than that of tillage radish. Unlike the other cover crop treatments, cereal rye in monoculture recovered significantly more Zn as the fertilizer N rate increased, which reflects the effect of fertilizer N rate on growth and dry matter accumulation by cereal rye.

In the 2015-2016 growing season, the main effects of cover crop treatment and fertilizer N rate significantly influenced the mass of Zn recovered by cover crops (Table 4-3). When averaged across fertilizer N rates, Zn uptake by cover crops and native weeds ranged from 25 to 153 g Zn ha^{-1} (Table 4-2). Planted cover crops recovered at a minimum nearly three times more Zn than volunteer weeds in fallow plots (Table 4-2), which indicates that managed cover crops can be effective at mining and storing soil Zn. Tillage radish recovered 153 g Zn ha^{-1}, which was 30% more Zn than cover crops in the blend and 220% more Zn than cereal rye (Table 4-2). Despite similar amounts of dry matter accumulated by established cover crops, cereal rye accumulated the least amount of Zn of all cover crops in the 2015-2016 growing season (Table 4-2). Investigating the differences in root growth between tillage radish and cereal rye could provide insight into the Zn recovery trends observed since studies like that of Kristensen and Thorup-Kristensen (2004) found that tillage radish roots can grow deeper into the soil than cereal rye roots. Applying fertilizer N to cover crops also facilitated greater Zn uptake by cover crops, and when averaged across cover crop treatments, Zn uptake ranged from 92 to 114 g Zn ha^{-1}

(Table 4-2). Cover crops recovered significantly greater masses of Zn when at least 67 kg N ha^{-1} was applied. Results from this study align with the findings of Kutman et al. (2011), who reported that high rates of N fertilizer facilitated greater Zn uptake by Durum wheat (*Triticum durum* cv. Balcali2000), especially when high N amounts (approximately 165 kg N ha^{-1}) were applied.

Phosphorus Uptake by Corn

The cover crop species significantly influenced the mass of P acquired by corn at the V6 growth stage in both years of this study (Tables 4-1, 4-3). In the 2014-2015 growing season, corn P uptake ranged from 0 to 5 kg P ha^{-1} (Table 4-4) and mirrored the trends observed with corn biomass production. Leikam et al. (2010) proposed that high yielding (19.3 Mg ha^{-1}) corn requires 3.5 kg P ha^{-1} by the V8 growth stage. In this study, only corn planted into tillage radish residue recovered a sufficient amount of P at the V6 stage as suggested by Leikam et al. (2010). Corn dry matter production and P uptake were greatest when corn followed tillage radish and least when corn followed cereal rye. When compared to corn planted into fallow, tillage radish contributed 3 kg P ha^{-1} to the subsequent corn, while cover crops in the blend did not increase P uptake by the following corn crop (Table 4-4). Cereal rye decreased the recovery of P by the subsequent corn crop by 1 kg P ha^{-1} when compared to no cover crop (Table 4-4).

In the 2015-2016 growing season, P uptake by corn ranged from 1 to 2 kg P ha^{-1} (Table 4-4) and, again, reflected the amount of dry matter accumulated by corn. None of the corn in the 2015-2016 growing season recovered sufficient amounts of P, according to the threshold for high yielding corn proposed by Leikam et al. (2010). Tillage radish maximized corn P uptake by recycling 1 kg P ha^{-1}, when compared to no cover crop (Table 4-4). Based on data and observations collected in this study, the increase in P uptake following tillage radish is likely a result of rapid decomposition and release of available P from the cover crop residue. The average C:P ratios for tillage radish in monoculture were 41 and 55 for the first and 2015-2016 growing seasons, respectively (data not shown), which is less than 200:1, the largest C:P ratio at which net P mineralization is expected to occur (Dalal, 1977). Carbon to P ratios of the blend and cereal rye in monoculture were 89 and 126, respectively, in the 2014-2015 growing season and 72 and 121, respectively, in the 2015-2016 growing season (data not shown). Although the C:P ratios were greater in the cover crop blend and cereal rye residues than in tillage radish residues, the values were still below 200:1, which would indicate that net P mineralization was possible. However, the limited soil contact and slowed decomposition diminished the transformation of organic P to inorganic P, rendering it unavailable for uptake by the corn crop. Furthermore, earlier termination of cover crop residue and earlier corn planting lead to early corn growth coinciding with cooler temperatures, which likely slowed root growth and P uptake by corn (Mackay and Barber, 1984).

Concentrations of P in corn shoots at the V6 growth stage were within the sufficient range (0.4 to 0.6%) (Campbell and Plank, 2000) for early-season corn regardless of cover crop treatment in the 2014-2015 growing season; however, corn planted after tillage radish and the cover crop blend contained P concentrations slightly below the sufficiency range in the 2015-2016 growing season (data not shown, calculated from biomass and P uptake data). Earlier termination in the warmer growing season likely limited nutrient uptake by cereal rye since a majority of the dry matter production and nutrient acquisition occurs in the spring for cereal rye (Finney et al., 2016). Results from this study contrast that of White and Weil (2010), who observed that corn following tillage radish did not produce significantly more dry matter at the V4 growth stage than corn following cereal rye in five out of six site years. White and Weil

(2010) also found that tillage radish did not significantly increase the concentration of P in aboveground biomass of the following corn at the V4 growth stage when compared to cereal rye in four out of six site years. However, research by Wang et al. (2008) showed that the available P content in the soil following oilseed radish was 10% greater than in soil following a grass cover crop (sorghum sudangrass (*Sorghum bicolor x S. sudanense* ‘Honey Sweet’)) and 15% greater than in soil following no cover crop.

Potassium Uptake by Corn

The mass of K recovered by corn in the 2014-2015 growing season was at least 2 kg K ha^{-1} and at most 54 kg K ha^{-1} (Table 4-4), which is less than the 55 kg K ha^{-1} uptake threshold at the V8 growth stage for high yielding corn recommended by Leikam et al. (2010). Tillage radish maximized K uptake by the following corn by contributing 43 kg ha^{-1} of recycled K (Table 4-4); since K recovery by tillage radish averaged 34 kg K ha^{-1}(Table 4-3), all of the K captured by tillage radish was likely made available for subsequent corn recovery. Similar to the results observed for P recovery by corn, planting corn into cereal rye residue resulted in a decrease in the amount of K recovered by corn at the V6 growth stage (Table 4-4). In the 2014-2015 growing season, cereal rye recovered, at most, 152 kg K ha^{-1}, while the following corn only recovered 2 kg K ha^{-1}. Given that K release is a function of leaching rather than decomposition (Marschner, 1995), the limited K uptake by corn following cereal rye is likely due to limited N availability.

In the 2015-2016 growing season, corn K uptake at the V6 stage ranged from 6 to 26 kg K ha^{-1} (Table 4-4), which is below the proposed level of K uptake at the V8 stage needed for high yield corn (Leikam et al., 2010). Tillage radish significantly increased corn K recovery compared to the blend and no cover crop. When compared to corn planted into fallow soil, tillage radish recycled 20 kg K ha^{-1}, which was nearly twice the amount recycled by the cover crop blend (Table 4-4). Corn following tillage radish recovered approximately 20% of the K that was recovered by the respective cover crop, which could indicate that tillage radish residue relinquished all of the captured K for subsequent uptake by the corn. Even though the blend was dominated by tillage radish biomass in the 2015-2016 growing season, and cover crops in the blend sometimes recovered greater amounts of K than tillage radish, a majority of the K recovered by cereal rye in the blend was likely retained in the cover crop residue. The K trapped in the cereal rye residue within the cover crop blend could account for the lower contribution of K from the two-way cover crop blend to the following corn crop. In both growing seasons, shoot K concentration for corn following no cover crop was within that of the sufficiency range (3 to 4%) (Campbell and Plank, 2000) for early season growth, while corn planted into cover crops contained K concentrations that exceeded the sufficient range (data not shown, calculated from biomass and K uptake data). The above adequate K concentrations of corn planted into cover crops implies that K was readily available to the following corn early in the growing season, which is expected since K is not bound in structural plant components (Marschner, 1995) and is readily leached from plant residue (Schomberg and Steiner, 1999).

Zinc Uptake by Corn

Zinc recovery by corn ranged from 1 to 22 g Zn ha^{-1} (Table 4-4) and followed trends similar to that of P and K uptake in the 2014-2015 growing season. Tillage radish in monoculture was the only cover crop treatment that significantly increased Zn uptake by the following corn crop, when compared to no cover crop, which was a result of 18 g ha^{-1} of Zn that was recycled by tillage radish (Table 4-4). Corn planted into the cover crop mixture recovered similar amounts of Zn as corn planted into fallow, while corn following cereal rye captured less Zn than corn following any other cover crop treatment. In the 2015-2016 growing season, corn recovered at least 2 g Zn ha^{-1} when planted into no cover crop and at most 8 g Zn ha^{-1} when following tillage radish (Table 4-4). Tillage radish maximized corn Zn recovery and recycled twice as much Zn to the following corn than cover crops in the blend, when compared to corn uptake following no cover crop (Table 4-4). When planted in monoculture, tillage radish recovered more Zn than cover crops in the cover crop blend, which could have provided more plant available Zn upon decomposition for the subsequent corn to utilize. Greater dry matter accumulation of corn that followed tillage radish and faster Zn release from tillage radish residue could have resulted in greater Zn recovery by corn. Zinc concentrations in corn shoots were below the sufficiency range (20 to 60 ppm) (Campbell and Plank, 2000) for early season corn, except that of corn following tillage radish in the 2014-2015 growing season (data not shown, calculated from biomass and Zn uptake data). Tillage radish has some potential to supplement some of the early-season Zn requirement for corn produced in the Mid-South; however, more studies are needed to examine the extent to which tillage radish and other similar cover crops affects the nutrient status of the following corn throughout the growing season and across growing conditions and production systems.

CONCLUSIONS

The mass of P, K, and Zn captured by cover crops reflected biomass production in the 2014-2015 growing season. Greater frequency of low temperatures below -4°C limited dry matter production by tillage radish, which diminished the timeframe and capacity of P, K, and Zn uptake for tillage radish in the 2014-2015 growing season. Cereal rye, on the other hand, was not susceptible to winterkill, which allowed for greater removal of residual P, K, and Zn from the soil in the spring. Overall, the application of N fertilizer did not have a positive effect on the recovery of P, K, and Zn by tillage radish but facilitated greater uptake of nutrients by cereal rye. Fertilizer N encouraged greater dry matter production by cereal rye, which increased the recovery of P, K, and Zn and the capacity to store those nutrients. The application of fertilizer N seemed to increase the susceptibility of tillage radish to winterkill, which limited growth and nutrient acquisition in the 2014-2015 growing season.

In the 2015-2016 growing season, differences in P, K, and Zn recovery by cover crops did not mirror that of cover crop dry matter production. While planted cover crops accumulated similar amounts of biomass, on average, P, K, and Zn uptake was generally greater for tillage radish and the tillage radish-dominated blend than for cereal rye alone. Belowground growth of cereal rye was not measured in this study, which might account for differences in nutrient recovery in the 2015-2016 growing season. The application of high rates of fertilizer N facilitated greater uptake of Zn by cover crops, but did not result in significantly greater cover crop recovery of P and K.

Corn P, K, and Zn recovery was only influenced by the cover crop and paralleled the amount of dry matter accumulated by corn at the V6 growth stage in both growing seasons. Tillage radish maximized biomass accumulation and P, K, and Zn uptake by corn in both growing seasons, which can be attributed to the rapid decomposition and nutrient release from tillage radish residue. Cereal rye, on the other hand limited the uptake of P, K, and Zn by the following corn crop by limiting N availability. Blending tillage radish with cereal rye increased P, K, and Zn uptake, when compared to no cover crop, only in the 2015-2016 growing season due to a greater portion of the blend comprised of tillage radish dry matter.

Results from this study indicate that fall and winter growing conditions and cover crop management can impact the ability of tillage radish and cereal rye to scavenge residual P, K, and

Zn in the Mid-South. Tillage radish acquisition of P, K, and Zn was limited by minimal dry matter production and premature termination due to persistently cold temperatures, but warmer temperatures maximized tillage radish biomass and nutrient accumulation. Uptake of P, K, and Zn by cereal rye was generally limited by N availability and early termination. Tillage radish consistently maximized corn uptake of P, K, and Zn by rapidly recycling available nutrients for the following young corn to utilize. Additionally, the deep-rooted taproot of tillage radish could have played other roles in facilitating greater uptake of P, K, and Zn by corn. In this no-till system, tillage radish likely increased corn uptake of the relatively soil-immobile nutrients by enabling deep soil layer scavenging by the roots, translocation to the shoots and enlarged fleshy taproot, and deposition of P, K, and Zn within the effective rooting depth of the young corn. Based on this study, corn in a Mid-South no-till system should be preceded by a quickly decomposing cover crop like tillage radish in order to maximize early-season recycling of P, K, and Zn. Further studies are needed to evaluate the timing of P, K, and Zn release from cereal rye and tillage radish in relation to corn nutrient demand throughout the season, as well as, the effect of P, K, and Zn release timing from the cover crops and those effects on yield of no-till corn in the Mid-South.

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TABLES

Table 4-1. Analysis of variance table for cover crop and corn uptake of P, K, and Zn in the 2014-2015 growing season at Kibler, AR.

Source	†Nparm	DFNum	DFDen	F Ratio	Prob > F
Cover Crop P Uptake					
Cover Crop	2	2	29.4	9.1	0.0008
Fertilizer N Rate	3	3	29.7	1.9	0.1556
Cover Crop by Fertilizer N Rate	6	6	29.8	5.7	0.0005
Corn P Uptake					
Cover Crop	3	3	41.0	128.1	<0.0001
Fertilizer N Rate	3	3	41.2	2.3	0.0922
Cover Crop by Fertilizer N Rate	9	9	41.2	1.3	0.2446
Cover Crop K Uptake					
Cover Crop	2	2	29.2	25.8	<0.0001
Fertilizer N Rate	3	3	29.9	2.7	0.0659
Cover Crop by Fertilizer N Rate	6	6	29.9	5.7	0.0005
Corn K Uptake					
Cover Crop	3	3	41.0	98.5	<0.0001
Fertilizer N Rate	3	3	41.2	2.4	0.0808
Cover Crop by Fertilizer N Rate	9	9	41.2	0.5	0.8833
Cover Crop Zn Uptake					
Cover Crop	2	2	29.6	6.0	0.0066
Fertilizer N Rate	3	3	30.0	2.8	0.0586
Cover Crop by Fertilizer N Rate	6	6	30.0	3.6	0.0085
Corn Zn Uptake					
Cover Crop	3	3	40.8	120.8	<0.0001
Fertilizer N Rate	3	3	41.0	1.5	0.2416
Cover Crop by Fertilizer N Rate	9	9	41.0	0.6	0.7710

† Nparm, number or parameters; DFNum, degrees of freedom for numerator; DFDen, degrees of freedom for denominator

Table 4-2. Mass of P, K, and Zn recovered by cover crops in the 2014-2015 and 2015-2016 growing seasons at Kibler, AR.

Cover Crop	Fertilizer N Rate	P†	K	Zn
	kg ha^{-1}			g ha^{-1}
2014-2015				
Tillage Radish	0	10 ef	34 d	49 de
	34	12 def	40 d	63 cde
	67	8 fg	29 de	45 e
	101	5 g	9 e	46 e
Tillage Radish/ Cereal Rye Blend	0	18 b	113 b	80 bc
	34	16 bcd	108 bc	68 bcd
	67	19 ab	118 b	85 ab
	101	20 ab	125 b	90 ab
Cereal Rye	0	13 cde	85 c	58 de
	34	16 bc	107 bc	78 bc
	67	19 ab	126 b	86 ab
	101	23 a	152 a	101 a
2015-2016				
Tillage Radish	0	35 a	147 abc	153 a
	34		134 bcd	
	67		127 cde	
	101		123 cdef	
Tillage Radish/ Cereal Rye Blend	0	29 a	147 abc	118 b
	34		162 a	
	67		159 ab	
	101		106 ef	
Cereal Rye	0	18 b	102 f	70 c
	34		103 ef	
	67		114 def	
	101		116 def	
Fallow	0	2 c	11 g	25 d
	34		13 g	
	67		20 g	
	101		26 g	
-	0	-	-	92 b
	34			101 ab
	67			114 a
	101			107 a

† Means followed by the same lowercase letter within a column for a given year and fixed effect are not significantly different at $P < 0.05$.

Table 4-3. Analysis of variance table for cover crop and corn uptake of P, K, and Zn in the 2015-2016 growing season at Kibler, AR.

Source	**Nparm†**	**DFNum**	**DFDen**	**F Ratio**	**Prob > F**
		Cover Crop P Uptake			
Cover Crop	3	3	43.2	50.0	<0.0001
Fertilizer N Rate	3	3	43.3	2.3	0.0892
Cover Crop by Fertilizer N Rate	9	9	43.3	1.4	0.2007
		Corn P Uptake			
Cover Crop	2	2	31.3	14.1	<0.0001
Fertilizer N Rate	3	3	31.6	1.6	0.2199
Cover Crop by Fertilizer N Rate	6	6	31.8	1.2	0.3473
		Cover Crop K Uptake			
Cover Crop	3	3	43.1	54.1	<0.0001
Fertilizer N Rate	3	3	43.2	1.4	0.2656
Cover Crop by Fertilizer N Rate	9	9	43.2	2.8	0.0109
		Corn K Uptake			
Cover Crop	2	2	31.2	25.0	<0.0001
Fertilizer N Rate	3	3	31.6	1.0	0.4188
Cover Crop by Fertilizer N Rate	6	6	31.7	1.2	0.3179
		Cover Crop Zn Uptake			
Cover Crop	3	3	43.3	37.2	<0.0001
Fertilizer N Rate	3	3	43.5	4.2	0.0105
Cover Crop by Fertilizer N Rate	9	9	43.6	1.4	0.2316
		Corn Zn Uptake			
Cover Crop	2	2	30.9	15.6	<0.0001
Fertilizer N Rate	3	3	31.2	1.8	0.1725
Cover Crop by Fertilizer N Rate	6	6	31.3	1.1	0.4099

† Nparm, number or parameters; DFNum, degrees of freedom for numerator; DFDen, degrees of freedom for denominator

Table 4-4. Corn uptake of P, K, and Zn following cover crops in the 2014-2015 and 2015-2016 growing seasons at Kibler, AR.

Cover Crop	P†	K	Zn
	kg ha^{-1}		g ha^{-1}
2014-2015			
Tillage Radish	5 a	54 a	22 a
Tillage Radish/ Cereal Rye Blend	2 b	13 b	5 b
Cereal Rye	0 c	2 c	1 c
Fallow	2 b	11 b	4 b
2015-2016			
Tillage Radish	2 a	26 a	8 a
Tillage Radish/ Cereal Rye Blend	1 b	16 b	5 b
Fallow	1 c	6 c	2 c

† Means followed by the same lowercase letter within a column for a given year and fixed effect are not significantly different at $P < 0.05$.

CHAPTER 5

Does Residue Incorporation Influence Available Nitrogen Release from Cereal Rye and Tillage Radish Cover Crops Under Controlled Conditions?

ABSTRACT

Nitrogen (N) captured by cover crops can be recycled for use by the following commodity crop via decomposition and net mineralization. Given the importance of synchronizing N mineralization with crop N demand, evaluating the magnitude and rate of N release from various cover crop residues is vital for maximizing N uptake efficiency and maintaining or improving overall crop productivity. Laboratory aerobic incubation experiments minimize variation in the potential mineralization from cover crop residues by controlling the soil moisture and temperature factors that heavily influence microbial activity and mineralization. This study assessed the magnitude of inorganic N released from tillage radish (*Raphanus sativus* L.) and cereal rye (*Secale cereale* L.) residue and to determine the influence of residue incorporation on N mineralization. The experiment was designed using a five by two factorial treatment structure with five cover crop residue treatments (tillage radish shoots, tillage radish roots, whole tillage radish, cereal rye shoots, and no cover crop) and two levels of residue incorporation (incorporated and surface applied). Cover crop residues were applied to a silt loam soil on an equivalent N basis, incubated for 25 wk and sampled periodically. Within the first 35 days, cover crops released as much as 12 mg NH_4-N kg soil^{-1} and 27 mg NO_3-N kg soil^{-1}. In general, NH_4-N release increased for 7 or 11 d after residue application, after which, NH_4-N release declined and NO_3-N concentration increased due to nitrification. Immobilization of N occurred the least in soil treated with tillage radish shoots, regardless of incorporation, and the most with incorporated cereal rye shoots during the first 35 d. Ammonium-N release during the later days (42 to 179 d after residue application) was negligible from tillage radish shoots and whole tillage radish residue, but cereal rye shoots and tillage radish roots released significant amounts of NH_4-N, which decreased over the last 137 d. Tillage radish roots released

significantly more NO_3-N from days 42 through 141 than any other residue, while cereal rye shoots released the least amount of NO_3-N from days 42 through 86. However, cereal rye shoots released NO_3-N at least three times faster than tillage radish shoots during the last 137 d of the study. The magnitude of NO_3-N released by each cover crop residue eventually converged 154 d after residue application, at which time the amount of NO_3-N released was not significantly different among cover crops. By the end of the study, 43% of the TN contained in the residues accumulated in the soil as NO_3-N, regardless of cover crop species or incorporation level. Results from this study indicate that incorporating cereal rye residue increases the occurrence of immobilization within the first 35 d after residue application; however, incorporation increases the rate at which NO_3-N is released from residues between 42 and 179 d after residue addition, regardless of cover crop species. Furthermore, N release from tillage radish shoots could coincide more closely with subsequent corn (*Zea mays* L.) N demand than cereal rye residue, and the most prevalent form of inorganic N available from cereal rye and tillage radish residues to the following corn crop during high N demand is NO_3-N.

INTRODUCTION

Living cover crops serve as temporary storage vessels for N remaining in the soil after cash crops are harvested, which reduces loss of N from the soil system (Jackson et al., 1993; Brandi-Dohrn et al., 1997; Parkin et al., 2006). After termination and upon decay, cover crops serve as N recyclers by relinquishing captured N that can be utilized by the next commodity crop. Some of the sequestered N can leach (mostly as NO_3-N) from cover crop residue and can be plant-available almost immediately (Miller et al., 1994), while much of the N assimilated in the residue must be mineralized to inorganic forms before being recovered by the following crop. The magnitude of soil inorganic N concentrations following cover crops and the timing of N mineralization in relation to crop N demand can have consequences on the growth, productivity, and supplemental fertilizer needs of the cash crop (Ruark et al., 2018). Cover crops have been shown to have positive, negative, or neutral effects on subsequent crop yield when compared to no cover crop (Decker et al., 1994; Kuo and Jellum, 2002; Andraski and Bundy, 2005; Dapaah and Vyn, 2008; Ruark et al., 2018). The extent to which N recycling by cover crops contributed to the following crop's N fertilizer needs has also been diverse among studies. Ruark et al. (2018) concluded that radish was an effective N catch crop but did not contribute significant N credits to the following corn crop. Andraski and Bundy (2005) observed that oat (*Avena sativa* L.), winter triticale (× *Triticosecale*), and cereal rye cover crops reduced the economic optimum N rate for the following corn by 32 kg N ha^{-1}, on average. Variability in yield and N credits due to cover cropping reflects the complexity of N cycling which stems from differences among soil environmental conditions, residue composition, and residue management. Mineralization is favored when soil conditions (temperature, moisture, aeration, pH, and salinity) are optimal for the growth and activity of soil microbes responsible for the aminization and ammonification processes (Cassman and Munns, 1980). In general, warm, moist soils provide the most favorable conditions for mineralization; however, even under ideal soil conditions, microbial conversion of organic N to inorganic N can be limited if sufficient N is unavailable to the microbes (Mullen, 2011).

Mineralization rate is often correlated with the C:N ratio and composition of the residue (Kuo et al., 1996). Residues that contain wider C:N ratios break down slower and encourage net immobilization of N, whereas residues with narrow C:N ratios decompose rapidly and facilitate net mineralization of N (Kuo et al., 1996). The C:N ratio of residue is largely determined by cover crop species but can vary with cover crop maturity and management (Wagger, 1989; Clark et al., 1997). While grass cover crop species such as cereal rye are commonly used as N scavengers, grass cover crops generally contain inherently wide C:N ratios and high concentrations of complex C structures, which often results in net immobilization or significantly delayed mineralization of organic N. Legumes and many *Brassica* species, on the other hand, contribute to rapid mineralization of N due to narrow C:N ratios and low lignin content. As a result, the release of available N from cover crops with narrower C:N ratios could potentially align more closely with the early season crop N demands than that of cover crops with wider C:N ratios (Jahanzad et al., 2016). Nitrogen mineralization from cover crops with wide C:N ratios can be improved by blending or adding cover crops with low C:N ratios and is oftentimes the justification for cereal and legume cover crop seed blends (Kuo and Sanju, 1998). Kuo and Sanju (1998) reported that mixing hairy vetch (*Vicia villosa* Roth.) residue (C:N=10:1) with cereal rye (C:N=23:1) or ryegrass (*Lolium multiflorum*) (C:N=24:1) decreased the overall C:N ratio of the mixture and increased net N mineralization compared to the respective cereal rye or ryegrass monocultures.

In addition to the amount of C and N contained in residue, the structural arrangement of C in plant residue can also limit mineralization. Structural polysaccharides such as cellulose and hemicellulose create a physical barrier that restricts microbial access to N and limits mineralization (Wagger, 1989; Bending et al., 1998; Mullen, 2011). Bending et al. (1998) determined that early N mineralization was largely influenced by soluble phenolic and water soluble N concentrations, while cellulose content regulated N mineralization during later stages of decomposition. In a study by Wagger (1989), the concentrations of cellulose and hemicellulose were consistently higher for cereal rye than crimson clover (*Trifolium incarnatum*

L.) and hairy vetch throughout the study, and consequently, cereal rye residue decomposed and released N slower than other cover crops.

Cover crop termination timing and residue placement can alter the rate at which N is mineralized and shift the alignment of N release in relation to crop N demand. In some cases, delaying cover crop termination allows cover crops to capture more N that could be recycled for the following cash crop; however, the C:N ratio of residue increases as plants mature, so postponing cover crop termination could also delay the release of N especially for species with inherently wide C:N ratios such as cereals (Wagger, 1989; Clark et al., 1997). Premature termination of cold-sensitive cover crops by subfreezing temperatures can lead to early release of N by leaching from residue, which could increase the amount of N available to the following crop early in the growing season or exacerbate N loss if leached N is not readily recovered (Miller et al., 1994; Dean and Weil, 2009). *Brassica* species, such as tillage radish and oilseed radish (*Raphanus sativus* (L.) var. oleifera DC Metzg), are commonly grown cover crops that are susceptible to winterkill in some regions. Previous studies have reported that inorganic N is prone to leaching from *Brassica* species residue following termination by low temperatures (winterkill). Miller et al. (1994) observed that at least 10% of the N in oilseed radish biomass was leached as NO_3-N or NH_4-N after residue was subjected to freezing (-18°C) and simulated rainfall. Management of cover crop residue after termination further influences the dynamics of N mineralization. Incorporating cover crop residue into the soil using tillage practices often accelerates N mineralization (Mitchell et al., 2000; Jahanzad et al., 2016) due to increased aeration and residue-to-soil contact. However, Aulakh et al. (1991) observed that incorporating residues with wide C:N ratios encouraged net immobilization more than surface application.

Given the complexity of N mineralization and variability in environmental conditions within a growing season, the precise timing and magnitude of available N resulting from mineralization can be difficult to predict. Controlling the temperature and soil moisture factors in a laboratory incubation experiment allows for examination of the potential magnitude and rate of N mineralized from various cover crop species. Understanding the inherent mineralization of N from cover crop residue under controlled conditions can provide preliminary information that can be assimilated into current cover crop recommendations for producers. Limited information exists on the potential N mineralization from cover crop residue in Arkansas soils. This study was conducted to investigate the influence of residue placement on the release of plant available N (NH_4-N and NO_3-N) from tillage radish and cereal rye cover crops.

MATERIALS AND METHODS

Experimental Design

An aerobic laboratory incubation of soil containing cover crop residue was conducted to assess the mineralization and nutrient cycling potential of cereal rye and tillage radish cover crops. The experiment was conducted over 25 wk, which corresponded with the average duration between cover crop termination in late March and corn harvest in mid-September in Mid-South corn production systems. The study was arranged in a randomized complete block design with a five by two factorial treatment structure consisting of five cover crop treatments (no residue control, whole tillage radish, tillage radish shoots, tillage radish roots, and cereal rye shoots) by two incorporation levels (incorporated and surface applied). Each treatment combination was randomly assigned a location in the incubation chamber within each sampling time and was replicated three times.

Laboratory Methods

Tillage radish and cereal rye residue and soil samples obtained from the 2015-2016 field study (Chapters 3, 4) at the Vegetable Research Station in Kibler, Arkansas were used in this incubation study. All cover crops were in vegetative growth stages at termination and sampling. Field soil used in this experiment for the growth of cover crops and for the aerobic laboratory incubation was classified as a Roxana silt loam (Coarse-silty, mixed, superactive, nonacid, thermic Typic Udifluvents) (Soil Survey Staff, 2015). Soil was collected from the top 15 cm adjacent to the plots in areas where cover crops were not planted and ^{15}N fertilizer was not applied.

Cover crop biomass samples were oven dried to a constant weight at 60°C, weighed, and ground to pass through a 2-mm sieve to obtain residue of uniform size. Soil samples were also air dried in the greenhouse at 23°C for 6 d, crushed by hand, passed through a 2-mm screen, and homogenized by inverting the soil in a cement mixer. Plant and soil subsamples were evaluated for total N and total C using automated dry combustion with an Elementar varioMax CN (Elementar Analysensysteme GmbH, Hanau, Germany) (Campbell, 1992). Additional plant subsamples (0.5 g) of each cover crop treatment were extracted with 0.3 L of 2 mol L^{-1} KCl and analyzed for extractable NO_3-N and NH_4-N using a SKALAR Segmented Flow Auto Analyzer (San System, Brenda, Netherlands). Chemical properties of residues including C:N ratio, extractable N, and TN are shown in Table 5-1. Soil texture was determined to be 280, 600, and 120 g kg^{-1} sand, silt and clay, respectively, using the hydrometer method (Huluka and Miller, 2014). Organic matter content for the soil was determined to be 1.1% by the loss on ignition (LOI) method by muffle furnace (Zhang and Wang, 2014). The pH of the soil was 6.8, and the inorganic N content, determined by a 2 mol L^{-1} KCl extraction and an autoanalyzer (Miller and Sonon, 2014), was 1.4 mg N kg $soil^{-1}$.

Particle size distribution and organic matter content were inserted into the Soil-Plant-Atmosphere-Water model to estimate the saturated water content (v6.02.75, USDA-ARS, Washington D.C.; Saxton and Rawls, 2006). Using the saturated water content and the assumption of a particle density of 2.65 g cm^{-3}, the bulk density of the soil was calculated to equal 1.53 g cm^{-3}. Based on results from the SPAW program, the estimated gravimetric water content for this soil that corresponded to -85 kPa was 0.17 g H_2O g^{-1} soil. The chosen matric potential is approximately 60% water-filled pore space, at which microbial activity for mineralization and nitrification is maximized (Linn and Doran, 1984). One hundred grams of dry soil was placed in plastic cups, and water was added to the soil to achieve a matric potential of -85 kPa, which was maintained throughout the duration of the incubation by weighing each cup and adding deionized water to achieve the appropriate total weight (soil + residue + water) every 5 d. Clear plastic wrap (Glad ® Press'n Seal, Glad Products Co., Oakland, CA) was loosely placed on top of incubation cups to reduce water loss via evaporation.

Prior to cover crop residue application, soils in the incubation cups were preincubated for 10 d at 23°C to allow soil microorganism activity to equilibrate. Cover crop residue was added to the soil and incorporated or applied to the soil surface and surface applied on an equivalent N basis (10 mg N ~ 100 mg N kg $soil^{-1}$). For the "whole tillage radish" treatment, tillage radish shoots and roots were applied at an N rate equivalent to 5 mg N each for a total of 10 mg N. A constant temperature of 23°C was maintained, which corresponded to the average mean soil temperature at Kibler, Arkansas from April to September. Extractions occurred every day for the first 4 d, every 4 d for the next eight sampling times, once a week for the following four sampling times, once every 2 wk for the next 2 mo, and then once a month for the final 2 mo. The sampling frequency was chosen to capture rapid changes in mineralization shortly after residue application and gradual changes throughout the time period corresponding to corn growth in the field. Since this process was destructive in nature, replicates of each sample were included for each sampling time. Entire soil + residue samples were placed in 2 L propylene bottles, and 1 L of 1 mol L^{-1} KCl solution was added. Mixtures were shaken for one hour and filtered through Whatman No. 2 filter paper. Extracted solution samples were subsequently refrigerated prior to analysis for NO_3-N and NH_4-N using a SKALAR Segmented Flow Auto Analyzer (San System, Brenda, Netherlands).

Data Analysis

The NO_3-N and NH_4-N from the untreated control soils averaged across the replications at each sampling time were subtracted from the respective results for each treatment replicate to obtain the net NO_3-N and NH_4-N released from the residue. The effects of cover crop type, residue management, and time on NO_3-N and NH_4-N release were analyzed using SAS 9.4 (SAS Inst., 2018, Cary, NC). Nitrate-N and NH_4-N data were analyzed separately, and data obtained from sampling every 4 d or less (0 to 35 d after residue application) were analyzed separately from data collected every 7 d or greater (42 to 179 d after residue application) for each form of N. Data collected within 0 to 35 d after residue application were analyzed using repeated measures to account for the possibilities of correlation or lack of independence between measurements taken closely in time or space (Gezan and Carvalho, 2018). A linear mixed model was fit for data collected within the 35 d after residue application using the PROC GLIMMX procedure with fixed effects of cover crop type, residue management, and time (days after residue application), and replication was a random effect. Significantly different means of each interaction in the repeated measures analyses were compared using an alpha level of 0.05.

Data for the remaining measurement times (42 to 179 d after residue application) were analyzed using a linear mixed analysis of covariance (ANCOVA) model. Cover crop type, residue management, and time were included in the ANCOVA model as fixed effects, while replication was considered a random effect. Each whole model included the random effect, three intercept terms (cover crop, residue management, and cover crop by residue management), and four slope terms (time, cover crop by time, residue management by time, and cover crop by residue management by time). Non-significant terms, as determined by a Type 3 fixed effects test at an alpha level of 0.05, were removed one at a time, beginning with the slope terms, and reanalyzed to obtain a reduced model that only contained significant terms. The slopes and intercepts of the respective significant terms were contrasted to separate significantly different slopes and intercepts at the alpha level of 0.05. The predicted means during time intervals at which the 95% confidence intervals appeared to overlap were analyzed compared at $P < 0.05$ to determine at which times the fitted lines converge and are no longer significant.

RESULTS AND DISCUSSION

Early N Release (Days 0 Through 35)

Within the first 35 d after residue application, NO_3-N and NH_4-N release were significantly influenced by all fixed effects (cover crop, residue management, and time) and their interactions (Table 5-2). Since extractable NO_3-N and NH_4-N accounted for at most 0.7 and 1.5% of the TN in the cover crop residue, respectively (Table 5-1), it can be assumed that direct leaching of NH_4-N and NO_3-N from residue contributed very little to the amount of N released, and mineralization and immobilization reactions largely governed the release of inorganic N to the bulk soil. In general, the amount of NH_4-N released from cover crop residue initially decreased from days 0 to 1, increased slightly from day 1 to day 2 or 3, decreased after day 7 or 11, and then remained relatively unchanged for each treatment (Table 5-3). Conversely, the amount of NO_3-N was initially low in days 0 to 7 and tended to increase after day 7 for most treatments (Table 5-4). Similar results were reported by Bending et al. (1998) who observed that NH_4-N was the dominant form of inorganic N during the first 7 d of incubation, and thereafter, NO_3-N was the most common form of mineral N released from plant residues. The opposite trends observed for NH_4-N and NO_3-N reflect that rapid N mineralization shortly after residue application produced NH_4-N, and as time progressed, much of the mineralized NH_4-N was rapidly nitrified to NO_3-N.

Negative values indicate the amount of NO_3-N or NH_4-N released from the residue is less than that from the non-treated control soils and reflects that net N immobilization likely occurred during that time. Within the NH_4-N results, a majority of the negative values occurred 23 d or more after residue application (Table 5-3). Incorporating cereal rye shoots into the soil resulted in the greatest occurrence of negative NO_3-N values within the first 35 d (Table 5-4), which implies that N was mostly immobilized by incorporated cereal rye shoots during the initial phase of sampling. Immobilization of N by cereal rye was expected since the residue composition of grass cover crops often limits mineralization (Ranells and Wagger, 1997; Rosencrance et al., 2000; Sievers and Cook, 2018). Negative NO_3-N values occurred the least when tillage radish shoots were added to the soil regardless of incorporation (Table 5-4), suggesting that tillage radish leaves readily mineralize N soon after application to the soil. Similar observations were seen by Aulakh et al. (1991), who reported that incorporating grass crop residues (corn and wheat (*Triticum aestivum* L.)) resulted in more immobilization of N than legume residues (soybean (*Glycine max* [L.] Meir.), and hairy vetch), especially within the first 17 d after residue application. The authors attributed the immobilization of N from the grasses to higher C:N ratios (82 and 39 for wheat and corn respectively); however, in this study, cereal rye shoots contained a C:N ratio of 18.2, which is below the threshold at which net immobilization typically occurs (>30:1) (Mullen, 2011). The difference in the occurrence of N immobilization between tillage radish and cereal rye shoots could likely be attributed to variations in the biochemical composition of *Brassica* and grass species. Trinsoutrot et al. (2000) showed that oilseed rape shoots (*Brassica napus* L.) contained nearly six times more soluble fractions and over four times less hemicellulose than grass species (wheat and barley (*Hordeum vulgare* L.)); consequently, the grass species immobilized more N during the 156 d incubation study than oilseed rape shoots. Similarly, Sievers and Cook (2018) observed that hairy vetch shoots contained four times less hemicellulose than cereal rye shoots, and as a result, hairy vetch shoots released eight times more N than cereal rye shoots over a 16-wk incubation.

The amount of net NH_4-N released from cover crop residues within the first 35 d ranged from -0.5 to 12 mg NH_4-N kg soil^{-1} (Table 5-3). Non-incorporated cereal rye shoots released the greatest amount of NH_4-N 3 d after residue application, while the least amount of NH_4-N was released by surface applied tillage radish roots 1 d after residue application. The addition of residue on day 0 resulted in the maximum NH_4-N release from all tillage radish treatments and incorporated cereal rye shoots for the first 35 d. Tillage radish shoots, roots, and shoots + roots relinquished, at most, 9.0, 3.0, and 4.4 mg NH_4-N kg soil^{-1}, respectively, when incorporated, and 7.6, 3.2, and 3.8 mg NH_4-N kg soil^{-1}, respectively, when retained on the soil surface (Table 5-3). On average, 2.3 times more NH_4-N was mineralized from tillage radish shoots than from tillage radish roots or whole tillage radishes on day 0, regardless of residue management. When residue was added on day 0, incorporated cereal rye shoots released 7.3 mg NH_4-N kg soil^{-1} (Table 5-3). Variability and release of NH_4-N directly from the residue during the extraction on day 0 could account for some of the relatively high initial concentration of NH_4-N. Non-incorporated cereal rye shoots, however, did not release the maximum amount of NH_4-N from the respective residue (12.0 mg NH_4-N kg soil^{-1}) until 3 d after residue application (Table 5-3); limited soil contact of the residue on the surface likely delayed mineralization from surface applied cereal rye shoots initially. For all treatments except surface applied tillage radish roots, the minimum amounts of NH_4-N mineralized from residue occurred after day 11, and the minimum values for each treatment were not significantly different among treatment interactions (Table 5-3). At day 35, the amount of NH_4-N mineralized from cover crop residue did not vary significantly among treatments and averaged 0.3 mg NH_4-N kg soil^{-1}.

For all treatments, residue management did not significantly affect NH_4-N release from each respective cover crop residue after day 11, when comparing NH_4-N at each sampling time within each cover crop treatment (Table 5-3). Tillage radish root NH_4-N release did not respond to residue management at each sampling time, while residue incorporation significantly decreased NH_4-N from tillage radish shoots and whole tillage radishes at two sampling times (days 3 and 11 for tillage radish shoots and days 2 and 3 for whole tillage radishes) (Table 5-3). Incorporating cereal rye shoots similarly decreased NH_4-N on days 1 through 7 (Table 5-3).

Nitrate-N release during the first 35 d ranged from -10.2 to 27.2 mg N kg soil^{-1} (Table 5-4). Tillage radish shoots (incorporated and surface applied) released the two greatest amounts of NO_3-N on day 35, while tillage radish roots released the two least amounts on days 23 and 27 (Table 5-4). At 35 d, the maximum NO_3-N release from each tillage radish treatment occurred, and tillage radish shoots relinquished 67% more NO_3-N, on average, than tillage radish roots, regardless of residue management (Table 5-4). Maximum NO_3-N from whole tillage radishes on day 35 was similar to that of tillage radish shoots and roots. Incorporated and surface applied cereal rye shoots released at most 17.5 and 24.2 mg NO_3-N kg soil^{-1}, respectively, on day 15 (Table 5-4), which occurred 15 and 12 d after the respective peaks in NH_4-N. On day 0 when NH_4-N was highest for most treatments, NO_3-N was negligible and averaged -0.2 mg NO_3-N kg soil^{-1} among treatment interactions. The minimum amount of relinquished NO_3-N from most treatments occurred before day 11, and NO_3-N release remained relatively steady and low during the first 7 or 11 d (Table 5-4). The low NO_3-N release within the first 11 d coincides with the relatively high release of NH_4-N, which indicates that nitrification was slow or did not occur at a rapid rate during this sampling time. The negative NO_3-N values that occurred 11 out of the 12 sampling times in the first 35 d for the incorporated cereal rye treatment implies that much of the N was immobilized.

When comparing NO_3-N values at each sampling time within each cover crop treatment, residue management resulted in varying effects. Similar to that observed for NH_4-N, residue management did not significantly affect the amount of NO_3-N relinquished by tillage radish roots at each sampling time (Table 5-4). Retaining cover crop residue on the soil surface resulted in increased NO_3-N from tillage radish shoots at day 3 and from whole tillage radishes at days 19 and 23 (Table 5-4). Residue management appeared to have the largest effect on NO_3-N from cereal rye shoots; incorporating cereal rye residue significantly reduced NO_3-N at 7 sampling times in first 35 d (Table 5-4). At most, incorporating cereal rye residue resulted in a decrease of 18.3 mg NO_3-N kg soil^{-1} suggesting high net immobilization (Table 5-4).

Since the recommended timing for cash crop planting in Arkansas is 2 to 4 weeks after cover crop termination (Roberts et al., 2018), the first 35 d of this incubation approximately corresponds to a time frame in which cover crop desiccation and decomposition occur, and little to no corn seedling emergence has occurred (Table 5-8). Given that corn N uptake is minimal during the first 20 d after emergence (< 10% of total uptake) due to relatively little root growth (Ritchie et al., 1996), results from this study indicate that as much as 27% of the TN contained in the cover crop residue could be susceptible to loss within the first 35 d after cover crop termination and prior to cash crop uptake. However, the particle size of residue used in this incubation study was 2 mm, which is likely much smaller than that of residue applied in no-till field conditions. Therefore, the rate of early N release observed in this incubation study is likely faster than that observed in the field.

The lag in net mineralization observed from incorporated tillage radish roots and incorporated cereal rye shoots is likely due to the structural composition of the cover crop residue and not the C:N ratio since the C:N ratio of the tillage radish roots (13.4) and cereal rye shoots (18.2) (Table 5-1) were lower than that of the predicted net mineralization threshold (20:1) (Mullen, 2011). Ruffo and Bollero (2003) demonstrated that slow residue decomposition and N release was associated more with high amounts of acid detergent fiber (ADF) and neutral acid detergent fiber (NDF) than with the total concentration of C and N; the authors concluded that the concentrations of soluble and recalcitrant fractions of residues provide an estimate of C and N availability to microbes, which might be more critical in governing mineralization than C and N concentrations. Sievers and Cook (2018) reported that the ADF and NDF concentrations of cereal rye shoots was 20 and 70% greater than that of hairy vetch shoots.

Late N Release (Days 42 Through 179)

The final model of NH_4-N release during the later days (> 42 d) included cover crop, time, and cover crop by time model terms (Table 5-5), which depicts that NH_4-N release varied significantly among cover crop treatments over time. Despite a lack of significance, the time term was necessary to retain in the model in order to run the model with the cover crop by time term. The linear model for NH_4-N release contained slope and intercept terms for each cover crop treatment, since the cover crop by time term was significant. Although the intercept for these lines cannot be literally interpreted as the amount of NO_3-N released at day 0, the intercepts can provide the relative vertical position of the lines or the relative magnitudes of NH_4-N or NO_3-N that was present at day 42. In the context of this study, the slope terms for each fitted line reflect the linear rate of N release in mg N kg soil^{-1} day^{-1}. The slope and intercept terms of the fitted lines for tillage radish shoots and whole tillage radish were not significantly different from zero (Table 5-6), which indicates that the amount of NH_4-N released from tillage radish shoots and whole tillage radishes did not vary significantly across the final 137 d of the study. The mean NH_4-N released from tillage radish shoots and whole tillage radishes was not significantly different from zero (at $P < 0.05$) for most of the sampling times (data not shown). The results for tillage radish shoots and whole tillage radish show that no net NH_4-N was released from these residues during the last 137 d of the study. Any NH_4-N mineralized from the tillage radish shoots or whole tillage radish residues was likely nitrified within the time between extractions, which were 7 to 30 d apart.

The fitted regression lines for NH_4-N released from tillage radish roots and cereal rye shoots contained intercepts greater than zero and slopes less than zero (Table 5-6), signifying that the amounts of NH_4-N released from these residues were initially high on day 42 and decreased over the last 137 d. Comparison of means among the cover crop treatments at day 42 and day 179 confirm the negative trend observed for cereal rye shoots and tillage radish roots during the later days of the study. On day 42, the means of NH_4-N for cereal rye shoots and tillage radish roots were 0.3 and 0.1 mg N kg soil^{-1}, respectively, which were significantly greater than zero (data not shown). By the end of the study, the means decreased to -0.04 and -0.05 mg N kg soil^{-1}, respectively, which were not significantly different from zero (data not shown).

The reduced model for NO_3-N released in the later days of the incubation included cover crop, residue management, time, cover crop by time, and residue management by time terms (Table 5-7), which indicates that the quantity of NO_3-N released varied significantly among cover crop treatments and between residue management treatments over time. Nitrate-N tended to increase linearly with time over the last 137 d for all cover crop treatments (Fig. 5-1). The intercept of the fitted line for NO_3-N release from tillage radish shoots was the greatest at 29.7 mg NO_3-N kg soil^{-1} (Table 5-6), which illustrates that NO_3-N from tillage radish shoots was initially greater than all other residues at day 42. Comparison of the predicted means at day 42 confirmed that tillage radish shoots released 32.7 mg NO_3-N kg soil^{-1} (data not shown), which significantly exceeded that of all other cover crop treatments. The fitted line for cereal rye shoots was comprised of the least intercept (4.18 mg NO_3-N kg soil^{-1}, Table 5-6), which reflects that cereal rye shoots released the least amount of NO_3-N (13.9 mg N kg soil^{-1}, data not shown) at day 42. Intercept (Table 5-6) and mean NO_3-N values for tillage radish roots at day 42 were also significantly lower than that of tillage radish shoots, which implies that N release from the roots was likely delayed compared to that from the shoots. Bending et al. (1998) found that roots generally contained less water-soluble fractions, which promote decomposition and N release, and more recalcitrant fractions (cellulose and lignin), which limit N release, than shoots. Given that the root and shoot portions of tillage radish contained similar C:N ratios (Table 5-1), the lag in N release observed from the root portion is likely due to the biochemical composition of the root residue that limited N availability to microbes.

The slope of the fitted line for cereal rye shoots (0.23 mg N kg soil^{-1} d^{-1}) was the greatest among the cover crop treatments (Table 5-6), implying that the rate of NO_3-N release from cereal rye was greater than that of any other residue across the final 137 d of the study. The fitted line for NO_3-N released by tillage radish shoots was comprised of the least slope at 0.07 mg N kg soil^{-1} d^{-1} (Table 5-6), indicating that NO_3-N was released over 3 times slower from tillage radish shoots than cereal rye shoots between 42 and 179 d after residue application. Although the equations of fitted lines vary among cover crop treatments, the fitted lines eventually cross one another and converge (Fig. 5-1), which implies that the amount of NO_3-N released does not vary significantly among cover crop treatments for several time points within the final 137 d of the study. Initially, the fitted lines for each cover crop treatment were significantly different from one another (days 42 through 86), and the predicted mean NO_3-N released from tillage radish shoots was the greatest, followed by that of whole tillage radish, tillage radish roots, and then cereal rye shoots. However, on day 87 and thereafter, the predicted mean NO_3-N released from tillage radish roots and cereal rye shoots did not differ significantly. By day 125, the mean NO_3-N released by whole tillage radish was not significantly different from that of tillage radish roots, and 3 d later, whole tillage radish also did not significantly differ from cereal rye shoots. Tillage radish shoot residues released significantly more NO_3-N than any other cover crop residue between days 42 and 141. By day 142, the amount of NO_3-N released by tillage radish shoots did not differ from that of whole tillage radish, and by day 144, tillage radish shoots released a similar amount of NO_3-N as tillage radish roots, as well. Nitrate-N release did not differ significantly among cover crop treatments from day 154 through day 179, which suggests that the residues returned similar amounts of available N by 179 d after residue application, regardless of cover crop species, plant portion or the rate at which N was released.

The slope and intercept terms for NO_3-N released during the later days also differed significantly between residue management treatments (Table 5-6), implying that residue incorporation influenced N release from cover crop residue. The intercept of the fitted line for surface applied residues was significantly greater than that of incorporated residues, which reflects that the magnitude of NO_3-N released from surface applied residues exceeded that of incorporated residues at day 42. The estimated difference in NO_3-N released on day 42 was confirmed by comparison of the predicted means of NO_3-N released from incorporated and surface applied residue. The mean NO_3-N released on day 42 from incorporated residues was 19 mg N kg soil^{-1}, which was significantly lower that of surface applied residues (26 mg N kg soil^{-1}) (data not shown). Conversely, the slope of the fitted line for NO_3-N released from incorporated residues was approximately 38% greater than the slope of the line for surface applied residues (Table 5-6), which illustrates that incorporating the residues contributed to faster turnover of N to NO_3-N over the last 137 d of the study. Although the intercepts and slopes of the fitted lines for the residue management effects differ, the lines cross and eventually converged by day 179, implying that the amount of NO_3-N released by cover crops did not differ by residue management by the end of the study (Fig. 5-2). On day 142 and after, the mean NO_3-N released from incorporated residues was not significantly different from that of surface applied residues. Furthermore, the predicted means for NO_3-N released by incorporated and surface applied residues on the final day of the study were not significantly different and averaged 43 mg N kg soil^{-1}(data not shown), which illustrates that all residues, regardless of management, returned approximately 43% of the N contained in the cover crop biomass as plant available N by the end of the incubation.

From days 42 through 141, tillage radish shoots released the greatest amount of NO_3-N, regardless of residue management, and, on average, residues retained on the surface released greater amounts of NO_3-N than incorporated residues. The time period of 42 to 141 d after residue application roughly coincides with much of the vegetative growth stages (emergence through VT) and early reproductive stages (R1 through R5) of corn planted 28 d after cover crop termination or residue application (Table 5-8) (Ritchie et al., 1996; Espinoza, 2008). Hanway (1962) estimated that 75% of the total uptake of N occurs between planting and 1 week after silking (approximately the R2 stage (Ritchie et al., 1996; Espinoza, 2008)). Therefore, tillage radish shoots could potentially contribute to greater N availability to the following corn crop than tillage radish roots or cereal rye during corn growth stages in which N demand is relatively high, regardless of residue management.

CONCLUSIONS

Within the first 35 d, as much as 12 and 27% of the TN contained in the residue was released as NH_4-N and NO_3-N, respectively. The highest amounts of NH_4-N release occurred within the first 3 d after residue application, while the highest amounts of NO_3-N were present between 15 and 35 d after cover crop residues were added to the soil. During the first 7 d of incubation, NH_4-N was the primary form of inorganic N released by most cover crop residues, and by day 35, the amount of NH_4-N released approached zero. After day 11, the majority of inorganic N released by cover crops was NO_3-N, which tended to increase in magnitude through the duration of the study. A greater occurrence of negative net NO_3-N values than NH_4-N values were observed during the first 11 d, which likely indicates that net NH_4-N was released and then immobilized in the microbial biomass, unavailable for transformation to NO_3-N via nitrification. Based on the trends observed for NH_4-N and NO_3-N release during the first 35 d, it can be concluded that net nitrification began to occur and residue decomposition produced NO_3-N after 11 d for most of the residue-treated soils. Net immobilization of N during the first 35 d was most prevalent from tillage radish roots and cereal rye shoot residues that were incorporated.

Based on the results from this study, retaining cereal rye shoots on the surface, as is the case in no-till management, contributed to greater release of available N during the first 35 d after residue application than incorporating cereal rye shoots, despite a lag in mineralization when cereal rye shoots were retained on the surface. Furthermore, tillage radish shoots most consistently released, rather than retained, inorganic N during the first 35 d than cereal rye shoots, regardless of residue management. However, the more consistent release of NO_3-N by tillage radish shoots than cereal rye shoots during the first 35 d, during which the following corn crop is likely not accumulating any significant amount of N from the soil, could more likely contribute to N loss than cereal rye shoots.

Cover crop residue type and residue management also significantly influenced N release during the final 137 d of the study. By day 42 and thereafter, tillage radish shoots and whole tillage radish residue did not release significant amounts of NH_4-N, but did release significantly increasing amounts of NO_3-N; these results indicate that any N mineralized to NH_4-N was rapidly nitrified to NO_3-N within the 7 or more d between extractions during the later days of the incubation. On the other hand, tillage radish roots and cereal rye shoots released significant amounts of NH_4-N, which eventually converged to zero by the end of the study. The gradual decrease in NH_4-N recycled from tillage radish roots and cereal rye shoots in the final 137 d of incubation can be explained by the simultaneous increase in NO_3-N released from the residues.

Retaining tillage radish and cereal rye cover crops on the surface, as in no-till systems, could also provide more available N to the successive corn crop throughout the high N demand growth stages compared to incorporating the residues. However, incorporating the cover crop residues increased the rate at which NO_3-N was released during the final 137 d. In this study, differences in the magnitude and rate of N release were observed among cover crop species, plant portions, and residue management techniques. By the end of the study, which loosely corresponds with corn maturity, approximately 43% of the TN contained in the residues was released from cover crop residues regardless of species, plant portion, or residue management. Based on the results from this study, tillage radish could possibly be more effective at synchronous N release in no-till corn production systems in the Mid-South than cereal rye. Furthermore, tillage radish and cereal rye have the potential to provide similar amounts of inorganic N (on a mg N kg soil^{-1} basis) over the same period of time, but at different rates and timings of release.

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TABLES AND FIGURES

Table 5-1. Chemical properties of cover crop residue.

Residue	C:N†	Extractable NO_3-N‡	Extractable NH_4-N‡	TN	%TN as Extractable NO_3-N	%TN as Extractable NH_4-N
		mg N kg residue^{-1}			%	
Tillage Radish Shoots	16	130	383	243	0.5	1.5
Tillage Radish Roots	13	128	162	190	0.7	0.9
Whole Tillage Radish	14	173	277	224	0.7	1.2
Cereal Rye Shoots	18	29	118	193	0.1	0.6

† Ratio of total C to total N (TN), which were determined by automated dry combustion (Bremner, 1996).

‡ Extractable NO_3-N and NH_4-N were determined by extracting samples with 2 mol L^{-1} KCl.

Table 5-2. Analysis of variance table for fixed effects resulting from the repeated measures analysis of NH_4-N and NO_3-N accumulated during the early days (0 to 35 d after residue application).

			NH_4-N		NO_3-N	
Effect	**DFNum†**	**DFDen**	**F Value**	**Pr > F**	**F Value**	**Pr > F**
Cover Crop	3	14	56.84	<0.0001	160.71	<0.0001
Incorporation	1	14	101.49	<0.0001	158.71	<0.0001
Cover Crop by Incorporation	3	14	22.45	<0.0001	20.5	<0.0001
Time	11	176	211.58	<0.0001	334.92	<0.0001
Cover Crop by Time	33	176	17.46	<0.0001	58.82	<0.0001
Incorporation by Time	11	176	26.62	<0.0001	34.69	<0.0001
Cover Crop by Incorporation by Time	33	176	9.46	<0.0001	5.77	<0.0001

† DFNum, degrees of freedom for numerator; DFDen, degrees of freedom for denominator

Table 5-3. Ammonium-N released (mg N kg soil^{-1}) from cover crop residue in the first 35 d after residue application as influenced by the three-way interaction between days after residue application, residue type, and residue management.

Residue Management	**Time After Residue Application**	**Tillage Radish Shoots**	**Tillage Radish Roots**	**Whole Tillage Radish**	**Cereal Rye Shoots**
	D	mg NH_4-N kg soil^{-1}			
Incorporated	0	9.0 c†	3.0 fghijk	4.4 efg	7.3 d
	1	2.0 klmn	0.1 stuv	1.4 lmnopq	0.6 pqrstuv
	2	2.2 jklmn	2.6 hijkl	2.1 klmn	4.2 efg
	3	1.6 lmnopq	2.2 ijklmn	1.9 klmnop	2.3 hijklm
	7	3.6 fghi	2.9 ghijkl	1.6 klmnopq	1.7 klmnopq
	11	0.3 qrstuv	0.9 nopqrst	1.0 nopqrst	1.4 mnopqr
	15	0.0 stuv	0.3 qrstuv	0.3 qrstuv	0.1 stuv
	19	0.2 stuv	0.2 rstuv	0.6 pqrstuv	0.8 nopqrst
	23	0.3 qrstuv	-0.3 uv	0.2 rstuv	-0.2 tuv
	27	0.8 nopqrstu	0.3 qrstuv	1.0 mnopqrst	0.6 pqrstuv
	31	0.4 qrstuv	0.3 qrstuv	0.4 qrstuv	0.7 opqrstu
	35	0.2 stuv	0.3 qrstuv	0.4 qrstuv	0.7 pqrstu
Surface Applied	0	7.6 cd	3.2 fghijk	3.8 efgh	4.6 ef
	1	3.0 fghijk	-0.5 v	1.0 nopqrst	2.7 hijkl
	2	2.9 hijkl	3.5 fghij	4.1 efg	10.5 b
	3	3.0 ghijk	3.3 fghij	3.3 fghij	12.0 a
	7	2.3 hijklmn	3.5 fghij	3.2 fghijk	5.3 e
	11	2.1 klmn	1.9 klmno	1.5 lmnopq	2.0 klmn
	15	0.2 stuv	0.2 stuv	0.1 stuv	1.0 nopqrst
	19	0.3 qrstuv	0.4 qrstuv	0.6 qrstuv	0.6 pqrstuv
	23	-0.4 uv	0.4 qrstuv	0.7 pqrstu	0.6 pqrstuv
	27	1.1 mnopqrs	1.4 lmnopqr	2.3 hijklmn	0.6 pqrstuv
	31	0.4 qrstuv	1.4 lmnopq	0.7 opqrstu	0.2 qrstuv
	35	0.0 stuv	0.3 qrstuv	-0.1 tuv	0.3 qrstuv

† Means followed by the same lowercase letters are not significantly different at 0.05.

Table 5-4. Nitrate-N accumulated (mg N kg soil^{-1}) in soil from cover crop residue in the first 35 d after residue application as influenced by the three-way interaction between days after residue application, residue type, and residue management.

Residue Management	Time After Residue Application	Tillage Radish Shoots	Tillage Radish Roots	Whole Tillage Radish	Cereal Rye Shoots
	D	mg NO_3-N kg soil^{-1}			
Incorporated	0	0.7 lm†	-0.7 lmn	0.4 lmn	-0.9 lmno
	1	0.5 lmn	-7.0 opqr	-2.7 mnopq	-5.5 opq
	2	-1.0 lmno	0.7 lm	-0.6 lmn	-4.6 opq
	3	-3.8 opq	-0.1 lmn	-2.8 mnopq	-5.6 opq
	7	1.7 klm	-1.2 lmnop	-5.6 opq	-6.3 opqr
	11	17.2 bcde	-0.8 lmno	8.0 ghijkl	-2.9 mnopq
	15	19.1 bcde	5.5 ijklm	12.8 cdefgh	17.5 bcde
	19	16.5 bcdefg	8.3 fghijkl	-1.3 lmnopq	-8.9 opqr
	23	19.9 bcde	-10.2 r	-5.4 opq	-9.6 qr
	27	8.8 fghijkl	-10.1 qr	-1.1 lmnop	-9.2 pqr
	31	21.2 abcd	12.2 cdefghi	10.3 defghij	-9.3 pqr
	35	26.5 a	15.2 bcdefg	20.9 abcd	-3.0 nopq
Surface Applied	0	0.5 lm	-1.4 mnopq	0.2 lmn	-0.7 lmn
	1	-0.2 lmn	-8.2 opqr	-6.3 opqr	-5.0 opq
	2	2.3 jklm	1.7 klm	2.1 jklm	-2.1 mnopq
	3	1.4 lm	2.2 jklm	2.5 jklm	-1.5 mnopq
	7	0.4 lmn	2.0 jklm	-1.5 mnopq	4.6 ijklm
	11	17.4 bcde	5.9 hijklm	11.8 defghi	9.6 efghijk
	15	22.2 abc	9.3 fghijkl	15.8 bcdefg	24.1 ab
	19	22.4 abc	14.9 bcdefgh	15.3 bcdefg	9.4 efghijkl
	23	23.7 ab	-7.0 opqr	4.9 ijklm	4.6 ijklm
	27	7.8 ghijkl	-3.0 mnopq	5.6 hijklm	4.7 ijklm
	31	24.4 ab	10.0 efghijk	19.9 abcde	6.0 ghijklm
	35	27.2 a	16.9 bcdef	23.2 ab	11.5 defghi

† Means followed by the same lowercase letters are not significantly different at 0.05.

Table 5-5. Analysis of variance for the whole and reduced models of NH_4-N released in the later days (42 to 179 d after residue application).

	Whole Model				Reduced Model			
Effect	**DFNum†**	**DFDen**	**F Value**	**Pr > F**	**DFNum**	**DFDen**	**F Value**	**Pr > F**
Cover Crop	3	221	5.13	0.0019	3	229	5.21	0.0017
Residue Management	1	221	0.39	0.5311	-	-	-	-
Cover Crop by Residue Management	3	221	0.41	0.7438	-	-	-	-
Time	1	221	2.55	0.1118	1	229	2.60	0.1083
Cover Crop by Time	3	221	3.53	0.0157	3	229	3.59	0.0144
Residue Management by Time	1	221	0.76	0.3855	-	-	-	-
Cover Crop by Residue Management by Time	3	221	0.17	0.9148	-	-	-	-

† DFNum, degrees of freedom for numerator; DFDen, degrees of freedom for denominator

Table 5-6. Intercept and slope estimates of cover crop and residue management effects for the linear models of NH_4-N and NO_3-N accumulated in the later days (42 to 179 d after residue application).

	NH_4-N		NO_3-N	
	Intercept	**Slope**	**Intercept**	**Slope**
	mg N kg soil^{-1}	mg N kg soil^{-1} d^{-1}	mg N kg soil^{-1}	mg N kg soil^{-1} d^{-1}
		Cover Crop		
Tillage Radish Shoots	-0.01 b†‡	4.8×10^{-5} ab‡	29.69 a	0.07 d
Tillage Radish Roots	0.19 ab	-1.4×10^{-3} bc	10.71 c	0.18 b
Whole Tillage Radish	-0.02 b‡	1.1×10^{-3} a‡	18.94 b	0.13 c
Cereal Rye Shoots	0.38 a	-2.4×10^{-3} c	4.18 d	0.23 a
		Residue Management		
Incorporated	-	-	11.40 b	0.18 a
Surface Applied	-	-	20.36 a	0.13 b

† Means followed by the same lowercase letter are not significantly different at P < 0.05 for a given regression term within a given main effect.

‡ Not significantly different from zero at P < 0.10.

Table 5-7. Analysis of variance table for whole and reduced models of NO_3-N accumulated in the later days (42 to 179 d after residue application).

	Whole Model				Reduced Model			
Effect	**DFNum†**	**DFDen**	**F Value**	**Pr > F**	**DFNum**	**DFDen**	**F Value**	**Pr > F**
Cover Crop	3	224	52.05	<0.0001	3	230	52.10	<0.0001
Residue Management	1	224	34.52	<0.0001	1	230	34.55	<0.0001
Cover Crop by Residue Management	3	224	1.57	0.1984	-	-	-	-
Time	1	224	415.88	<0.0001	1	230	416.28	<0.0001
Cover Crop by Time	3	224	20.41	<0.0001	3	230	20.43	<0.0001
Residue Management by Time	1	224	11.27	0.0009	1	230	11.28	0.0009
Cover Crop by Residue Management by Time	3	224	1.04	0.3762	-	-	-	-

† DFNum, degrees of freedom for numerator; DFDen, degrees of freedom for denominator

Table 5-8. Estimated corn growth stage associated with days after residue application or cover crop termination.

Time After Residue Application/ Cover Crop Termination (d)	Estimated Corn Growth Stage
0 to 28†	-
33 to 49	Emergence
63 to 78‡	V6 to V8
78 to 102	V12 to V17
96 to 104	VT to R1
108 to 116	R2
118 to 128	R3
126 to 130	R4
132 to 142	R5
144 to 162	R6

† All values estimated assuming corn planting at 28 d after cover crop termination.

‡ Estimated values for V6 stage and beyond calculated based on the estimated days after emergence for each corn growth stage and the average days for seedling emergence of 42 d after planting as reported by Espinoza (2008).

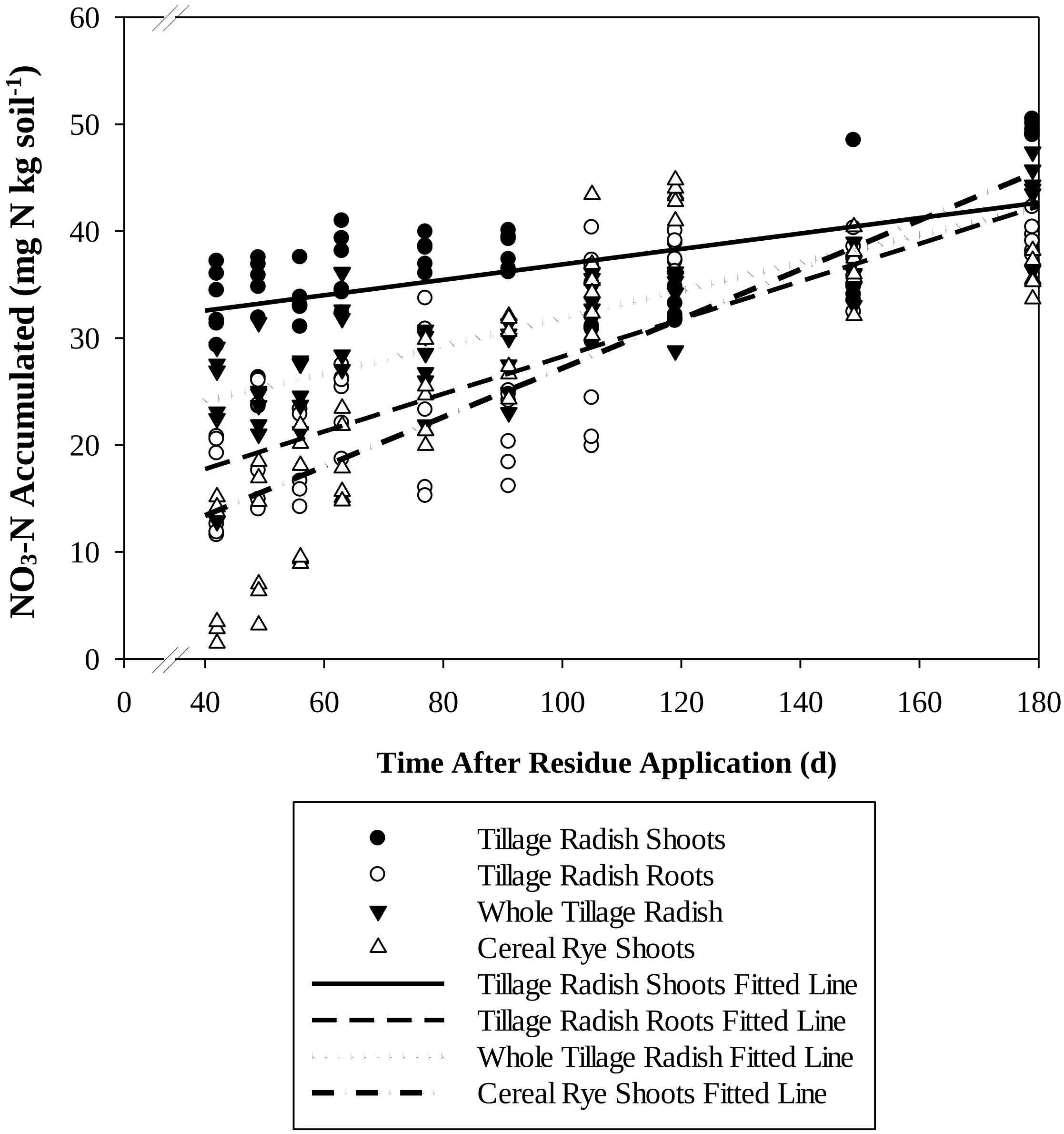

Figure 5-1. Scatterplot with fitted regression lines of NO_3-N accumulated during the later days (42 to 179 d) as affected by cover crop residue type.

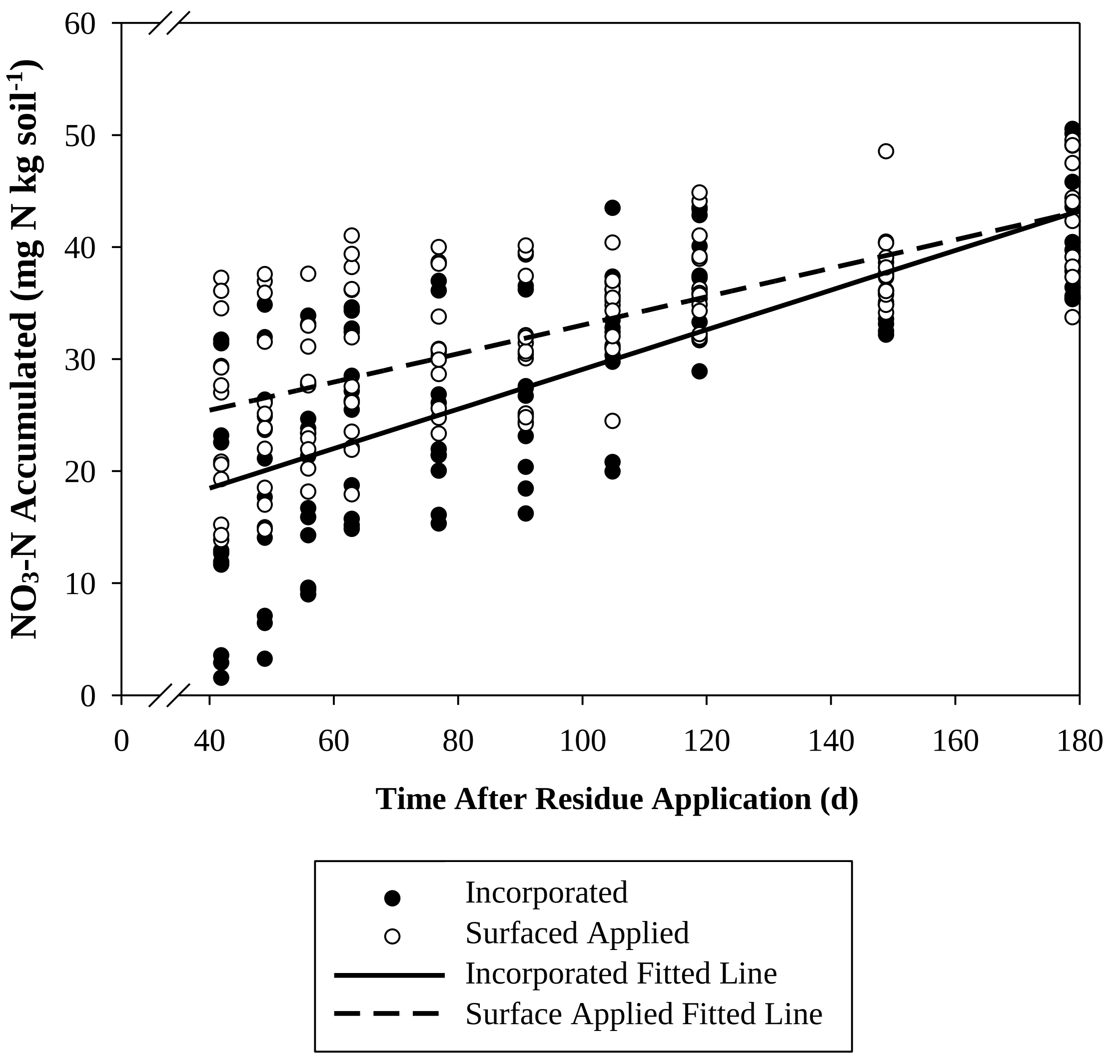

Figure 5-2. Scatterplot and fitted regression lines for NO_3-N accumulated during the later days (42 to 179 d) as affected by residue management.

CHAPTER 6

Conclusions

CONCLUSIONS

The overall goal of this research was to provide a comprehensive analysis of nutrient recycling by tillage radish (*Raphanus sativus* L.) and cereal rye (*Secale cereale* L.) cover crops as it relates to early-season nutrient recovery by a subsequent corn (*Zea mays*) crop. A greenhouse study was designed to evaluate N recovery by cover crops and trace the fate of nitrogen (N) within each cover crop under controlled environmental conditions (Chapter 2). The growing conditions and duration of the greenhouse experiment resembled conditions for cover crops planted in the fall and allowed to grow until winter dormancy in the Mid-South. Results of the greenhouse study showed that N uptake is highly dependent on biomass production, which varies among cover crop species and N availability. Tillage radish produced more shoot biomass than cereal rye within the three months of growth in the greenhouse, which reflects that tillage radish accumulates biomass more rapidly in the fall than cereal rye. However, cereal rye can potentially compensate for limited shoot growth and shoot N recovery with more root growth than tillage radish in the fall. Greater root biomass allows cereal rye to store greater amounts of N belowground in the fall than tillage radish. Regardless of species, most of the N recovered was translocated to the shoots and only a limited percentage of the total N (TN) recovered was fertilizer N.

The purpose of the field study was to investigate the efficacy of tillage radish and cereal rye cover crops to sequester and release plant-available nutrients (N, P, K, and Zn) for early-season uptake by the following corn crop. Similar to observations made in the greenhouse study, nutrient uptake was highly dependent on dry matter production. Tillage radish biomass and the resulting nutrient uptake were similar to or exceeded that of cereal rye when winter growing conditions were, on average, 3°C warmer than the previous growing season. Colder growing conditions, characterized by lower temperatures and over three times more days below -4°C during cover crop growth, led to winterkill of tillage radish, limited dry matter and nutrient accumulation, and possibly premature nutrient release from tillage radish residue. Regardless of differences in biomass accumulation or nutrient uptake by cover crops, nutrient release from tillage radish more closely aligned with early-season nutrient uptake by the following corn crop. Although tillage radish contributed a significant amount of nutrients to the subsequent corn, the quantity of recycled nutrients was not sufficient to fully substitute for the early-season N, P, K, or Zn requirements based on current recommendations for irrigated corn produced on silt loam soils in Arkansas. In general, corn following tillage radish produced more dry matter and accumulated more N, P, K, and Zn by the V6 stage than corn following cereal rye. It can be concluded that cereal rye immobilized or retained most of the nutrients throughout the early corn growth stages since nutrient uptake by corn planted into cereal rye residue was less than the winter fallow control (no cover crop). Based on these observations, additional early-season N fertilizer would be needed for the following corn crop to compensate for the N sequestered and retained by cereal rye.

The objective of the laboratory incubation study was to determine the potential inorganic N release from cereal rye and tillage radish residues under controlled conditions as it relates to corn growth stages and N demand. Data from the incubation study confirm that cereal rye limited N availability for corn early in the growing season by initially immobilizing N and releasing minimal amounts of inorganic N during the time that coincided with the early growth stages. Incorporating cereal rye residue facilitated greater immobilization of N within the first 35 days after residue application. Results from the laboratory support the conclusion made from the field study, suggesting that the timing of N release from tillage radish more closely aligns with early-season N uptake by corn. Plant available N release from tillage radish shoots exceeded that of cereal rye shoots from 42 to 153 d after residue application, which roughly coincides with the vegetative stages and early reproductive stages of corn when N demand is highest. By the end of the incubation, which approximately corresponded to the timing of corn maturity, cereal rye released similar amounts of N compared to tillage radish, and the amount of N released was less than half of the TN contained in the residue. Cereal rye compensated for low early-season N release with a faster N-release rate during the final 137 days of the study than tillage radish. Incorporating all cover crop residue increased the rate at which NO_3-N was released throughout the time that corresponded to corn growth following cover crops; however, the concentration of N released by cover crops by the end of the incubation study was similar, regardless of residue management. Results from this research indicate that timing of nutrient release from cereal rye and tillage radish cover crops differs significantly. Furthermore, incorporating cover crop residues will further expedite N release, but could potentially yield the same amount of N released by corn maturity.

Based on results from this research, corn should be preceded by tillage radish rather than cereal rye cover crops in order to reap the maximum N, P, K, and Zn recycling benefits early in the corn growing season. However, when erosion control and nutrient loss prevention are desired, cereal rye cover crops can be planted before corn without incurring additional early-season N fertilizer needs or sacrificing early season corn growth if cereal rye is mixed with tillage radish. Nitrogen fertilizer application is not recommended for tillage radish and cereal rye planted within optimal establishment windows on silt loam soils in Arkansas, since at least 32% of the applied fertilizer N was not recovered by cover crops, and fertilizer N did not significantly increase tillage radish biomass or early-season corn growth. Incorporating cover crop residue with light tillage can be used to increase the rate at which plant available N is released from the residue; however, incorporating cover crop residue with tillage can negate some cover crop benefits by accelerating organic matter degradation and exacerbating erosion.